NAVIGATION AND TRAFFIC CONTROL 11

Useful Applications of Earth-Oriented Satellites

NATIONAL ACADEMY OF SCIENCES
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SUMMER STUDY ON SPACE APPLICATIONS

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NAVIGATION AND TRAFFIC CONTROL

Prepared by Panel 11 of the
SUMMER STUDY ON SPACE APPLICATIONS
Division of Engineering
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for the
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PREFACE

In the fall of 1966, the National Aeronautics and Space Administration (NASA) asked the National Academy of Sciences to conduct a study on "the probable future usefulness of satellites in practical Earth-oriented applications." The study would obtain the recommendations of highly qualified scientists and engineers on the nature and scope of the research and development program needed to provide the technology required to exploit these applications. NASA subsequently asked that the study include an analysis of cost-benefit relationships.

Designated "The Summer Study on Space Applications," work began in January 1967, guided by a Central Review Committee (CRC) appointed by the Academy. The Study's Chairman was Dr. W. Deming Lewis, President of Lehigh University.

Technical panels were convened to study practical space applications and worked intensively for periods of two to three weeks during the summers of 1967 and 1968 at Little Harbor Farm in Woods Hole, Massachusetts. The work of each panel was then reported to the Central Review Committee, which produced an overall report. Panels were convened in the following fields:

Panel 1: Forestry-Agriculture-Geography

Panel 2: Geology

Panel 3: Hydrology

Panel 4: Meteorology

Panel 5: Oceanography

Panel 6: Sensors and Data Systems

Panel 7: Points-to-Point Communications

Panel 8: Systems for Remote-Sensing Information and Distribution

Panel 9: Point-to-Point Communications

Panel 10: Broadcasting

Panel 11: Navigation and Traffic Control

Panel 12: Economic Analysis

Panel 13: Geodesy and Cartography

The Panel on Navigation and Traffic Control compiled an interim report during the summer of 1967 under the chairmanship of General P. C. Sandretto, who was later forced to resign because of the pressure of his regular duties.

During the summer of 1968 the report was revised and prepared for publication under the guidance of Dr. Paul Rosenberg, the new chairman.

The major part of the Study was accomplished by the panels; the function of CRC was to review their work, to evaluate their findings, and, in the context of the total national picture, to derive certain conclusions and recommendations. The Committee was impressed by the quality of the panels' work and has asked that the panel reports be made available to specialized audiences. While the Committee is in general accord with the final panel reports, it does not necessarily endorse them in every detail. It chose to emphasize the major recommendations in its overall conclusions and recommendations, which have been presented in Useful Applications of Earth-Oriented Satellites: Report of the Central Review Committee.

In concluding this preface, it is emphasized that the conclusions and recommendations of this panel report should be considered within the context of the overall report of the Central Review Committee.

NAVIGATION AND TRAFFIC CONTROL PANEL

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CORRECTION

Panel 11: Navigation and Traffic Control
Useful Applications of Earth-Oriented Satellites

On page 84, the first sentence of Section 11.1 should read:

Design, build and test a developmental system to provide traffic-control service to en route transoceanic air traffic, confluence-area marine traffic, and en route navigation for ships, using geostationary satellites and ranging measurements for position determination.

1.0 INTRODUCTION

The rapid growth of air, sea, and land transportation is accompanied by acute problems in navigation and traffic control, both in this country and abroad. Existing systems for solving these problems are marginally satisfactory in some applications, inadequate in others. Earth-orbiting satellites offer possible solutions to some of these problems. The purpose of the Panel's work and report is to examine and evaluate the possible applications of earth satellites to national and international problems of all forms of navigation and traffic control.

A navigation and traffic control satellite has one undisputed and unique advantage over other systems for navigation and traffic control, namely, the satellite is geometrically situated so that it has direct lines-of-sight with vehicles and ground stations over a wide area of the globe.

Satellite systems can determine the positions of cooperating vehicles on the surface and in the air with a high accuracy and promptness that is useful in many applications.

However, the economic justification for establishing these satellite systems and the cost benefits to be derived are much more difficult to determine, and are explored in this report.

Only unmanned satellites have been considered in this study. Manned satellites are not necessary for navigation and traffic control, nor is their cost justified for this purpose.

Safety is the most important and direct benefit of traffic control of aircraft and ships. In air operations, improved enroute traffic control permits narrower air lanes and closer spacing of aircraft within the lanes with an acceptable level of safety, resulting in shorter routes and more efficient traffic flow. Analogous benefits are derived from safety in marine traffic, plus the reduction of losses due to collision.

2.0 SUMMARY

Satellites can be used for navigation and traffic control. More than 40 such applications were considered in this study.

Some of these applications are feasible with present technology. Others are likely to become feasible after further technology development.

The applications which are most practical and most urgent are:

Enroute traffic control of aircraft over the North Atlantic Ocean

Traffic control of surface vessels in confluence areas

Search and rescue at sea (air as well as marine)

On technical and engineering grounds, satellite systems are superior to systems now in use in the aforesaid applications. However, satellite systems are not better for terminal air traffic control and harbor traffic control.

The costs of a satellite system to provide en route transoceanic air traffic control only would exceed the benefits to be gained for many years. On the other hand, such a satellite could also provide improved operational and management communication services to aircraft; and these benefits might make the satellite system cost-effective at an earlier period.

The benefits received by the overall marine community from a satellite system to provide traffic control in confluence areas, and enroute navigation for ships, would exceed the costs of such a system. Most of these benefits would accrue to foreign-owned ships, because the U. S. -owned fleet is relatively small.

In general, the cost-benefit advantages to the maritime industry greatly exceed those to the aviation industry.

The earliest realizable operating system seems to be a single geostationary satellite over the North Atlantic, using VHF channels for ranging, to monitor the positions of aircraft approximately at right angles to their lanes. This system would use roll-call access, with an emergency channel. This could be followed by additional similar satellites to determine positions along-track as well as cross-track. UHF satellites of the same type might follow. Eventually, satellite systems which use angle-measurement techniques could replace the ranging systems.

A recommendation is made in this report for the development and test of a prototype satellite system to provide traffic control service to enroute transoceanic air traffic and to confluence-area marine traffic, and to provide en route navigation aid for ships. Recommendations are also made for further research and development, systems analysis and definition, and implementation planning, for satellite systems for navigation and traffic control.

3.0 DEFINITIONS

In this study and report, the term navigation means the process whereby a vehicle determines its position on or near the earth's surface, its direction and speed, and the direction of its intended travel to reach a destination.

The term traffic control is used herein to mean coordination of the movements of all vehicles in a specified space by a control agency, for the purpose of safety, efficiency and economy. The control agency must have surveillance means to monitor the positions of all vehicles in the specified space, means for rapid communication with each vehicle, and the ability to make decisions.

Terminal air traffic control is air traffic control in the vicinity of airports. En route air traffic control is air traffic control outside of the terminal area.

Marine traffic control is divided into harbor traffic control, traffic control in confluence areas, and traffic control on the high seas.

Vehicles include: ships and other surface vessels; subsurface vessels; hydrofoils; air cushion vehicles; all types of aircraft; automobiles, railroad trains, and other land vehicles; animals whose migration is to be studied; and unmanned sensors, the positions or movements of which are to be determined.

4.0 POTENTIAL APPLICATIONS

Navigation encompasses the guiding of a vehicle from its point of departure to its destination, and involves not only finding that destination, but avoiding obstructions and other vehicles. Safety is a major portion of navigation. The quality of navigation also affects the time enroute and the fuel expended. Navigation is an essential part of every passage from one point to another. Every voyage in history has had an element of navigation in it, and all future movements across the earth will also require navigation.

Traffic control is a modern notion that reflects the crowded conditions that are an increasing part of 20th century life. Air Traffic Control was established because the number of aircraft increased, their speed became greater, and they gained the capability of flying under conditions of reduced visibility. It became apparent that they could not by themselves prevent collisions with each other. An Air Traffic Control service over the United States was first established by the airlines, but for many years it has been operated by the Federal Government under authority of law. Control of the airspace over other nations is now generally administered by the respective governments. Control of oceanic airspaces throughout the world was assigned to the nations bordering on the oceans, by the conference which in 1943 established the International Civil Aviation Organization. At the present time there is no closed-loop air traffic control over the ocean comparable to that on land, nor is there a Marine Traffic Control Service. The desirability of such a service has been widely espoused as a means of reducing the hazards of collisions and grounding, but the technical limitations of position determination and communications, using ground-based systems, prevent the service from being established at present.

There are three main defects in the present navigation and traffic control service:

1. Inability of the present Air Traffic Control service to contend with the numbers of aircraft flying across the oceans, except by costly delays and diversions
2. Lack of a Marine Traffic Control service, and the rising marine insurance rates, which reflect the increase in costly collisions and groundings of ships
3. Need of higher-accuracy, worldwide, all-weather navigation information for ships, especially commercial fishing vessels

Satellites may provide the means to correct these defects.

4.1 The Need For Satellites

Earth satellites have a property not shared by other man-made objects. Their great altitude enables them to "see" very large regions of the earth, and they can therefore serve as relay points for line-of-sight radio propagation between widely separated points on the earth. Satellite motions can be tracked and their locations determined so accurately that they may be used as reference points for determining the positions of craft on the earth. The radio equipment that satellites carry to perform their functions has performance characteristics like radio equipment used for similar purposes in earth-based applications. The techniques for using them as references for position-fixing are well known.

This unique characteristic makes satellites especially attractive for navigation and traffic control over large regions of the earth or for numerous smaller regions dispersed throughout a large area where each of the smaller regions is in itself too large to be covered economically by direct line-of-sight ground-based systems such as radars.

It has been demonstrated that satellites can provide the advantages of line-of-sight communications between mobile craft and distant ground stations. The reliability and quality of the satellite communications are much better than the only alternative – the use of high-frequency radio propagation by ionospheric reflection. HF radio is so unreliable and of such poor quality that it cannot be depended upon for a closed loop traffic control system.

When satellites are used for transoceanic traffic control, they offer great flexibility for changes in routes. Whereas a line of sea stations across the ocean could provide line-of-sight communication to aircraft, and relay the communications by cable, microwave relay, or HF radio, the route would be inflexible, and its expansion would be expensive. Satellites can see an entire ocean basin at one time, and can be used over all the routes covering the ocean, allowing day-to-day changes in routes as might be desired due to changing weather conditions.

Marine traffic control will be concentrated in a number of ocean regions which are confluence areas for shipping. All of the confluence areas in an ocean basin such as the Atlantic could be accommodated by a single system, whereas radar coverage to provide traffic control for all these areas would require a very large number of installations. The ground-based system again would be inflexible, whereas the satellite system would provide great flexibility. Furthermore, the satellite system can provide additional traffic surveillance over the entire ocean, so that it can provide weather routing and other services in regions wherever these services are called for, and regardless of the fact that the geographical locus of such regions of need may change within a short period of time.

No ground-based system or combination of systems appears to offer the functions of position surveillance and undelayed communications over large and changing regions of the earth's surface as effectively as a satellite system.

4.2 Applications Considered

Earth-oriented navigation and traffic control applications of space technology were examined for the purpose of identifying those likely to be of maximum benefit.

A graphic method for summarizing the potentialities of more than 40 space technology applications was developed and a series of charts prepared. These charts are directed to three time frames. The first period is from 1970 to 1975. This time frame is essentially that of sub-sonic aircraft. Operational requirements are assumed to change with the advent of the supersonic transport in 1975, and this epoch is expected to be in full swing to 1982. The period beyond 1982 is one in which only the imagination serves as a guide to requirements and improved technology.

Each application was rated in terms of technical feasibility, need, economics, and suitability to accomplishment by satellite. The results are shown in the following tabulation with its accompanying explanation of the notation used.

NOTATION

Used in the columns under T, N, E, and A, respectively, in the table of "Possible Satellite Applications" on the following 4 pages.

T = Technical Feasibility

1a = Technically feasible with the technology at the beginning of the time period with no further R&D

1b = Technically feasible within the time period with R&D

2 = Marginally feasible

3 = Not technically feasible

N = Need

1a = Needed now

1b = Needed at end of period

2 = Marginal need

3 = Not needed

E = Economic Justification:

1a = Economically justified on its own, without any other uses of the satellite system

1b = The incremental cost of the satellite system for this use is justified provided the principal cost of the satellite is justified by other uses.

2 = Justification is marginal, even under the conditions of E1b.

3 = Not justified economically

A = Best Accomplished by:

S = Satellite

O = Other systems

TABLE 11.4.1

POSSIBLE SATELLITE APPLICATIONS

	1970 to 1975				1975 to 1982				Beyond 1982			
	T	N	E	A	T	N	E	A	T	N	E	A
COMMUNICATIONS												
<u>Surface vehicles</u>												
<u>Marine</u>												
*Traffic control including collision avoidance between ships												
a. High Seas	1b	1b	1b	S	1a	1a	1a	S	1a	1a	1a	S
b. Confluence Areas	1a	1a	1b	O	1a	1a	1a	S	1a	1a	1a	S
c. Harbors	-	1a	-	O	-	1a	-	O	-	1a	-	O
Weather information exchange and related advisories, e.g., proximity warning of icebergs, floating hulks, etc.	1a	1a	1a	S	1a	1a	1a	S	1a	1a	1a	S
Communications for public use	2	1a	1b	S	2	1a	1b	S	1a	1a	1b	S
Operational communications and communications for management control	1b	1a	1b	S	1a	1a	1b	S	1a	1a	1b	S
Data communications with unmanned sensors	1b	1b	1b	S	1a	1a	1b	S	1a	1a	1b	S
Search and rescue (including distress reporting)	2	1a	1a	S	1a	1a	1a	S	1a	1a	1a	S
AMVER (Automated Merchant Vessel Reporting)	-	2	-	O	*Combines with traffic control in these time periods.							

(Table continues on next page)

*See para. 4.3.4.

TABLE 11.4.1 (continued)

	1970 to 1975				1975 to 1982				Beyond 1982			
	T	N	E	A	T	N	E	A	T	N	E	A
Ground												
Studies of animal migration	-	3	-	O	-	2	-	O	-	2	-	O
Exploration, including mineral search	-	3	-	O	-	3	-	O	-	2	-	O
Data communication with unmanned sensors	1b	1b	1b	S	1a	1a	1b	S	1a	1a	1b	S
Aircraft												
Traffic control en route	1b	1a	1a	S	1a	1a	1a	S	1a	1a	1a	S
Terminal air traffic control	-	1a	-	O	-	1a	-	O	-	1a	-	O
Collision avoidance and proximity warning, independent of air traffic control	-	1a	-	O	-	1a	-	O	-	1a	-	O
Weather information exchange and related advisories regarding conventional meterology, clear air turbulence, and radiation	1a	1a	1b	S	1a	1a	1a	S	1a	1a	1a	S
Communications for public use	2	1a	1b	S	1b	1a	1b	S	1a	1a	1b	S
Operational communications and communications for management control	1b	1a	1b	S	1a	1a	1b	S	1a	1a	1b	S
Data communications with unmanned sensors	1b	1a	1b	S	1a	1a	1b	S	1a	1a	1b	S

(Table continues on next page)

TABLE 11.4.1 (continued)

	1970 to 1975				1975 to 1982				Beyond 1982			
	T	N	E	A	T	N	E	A	T	N	E	A
Search and rescue (including distress reporting)	2	1a	1a	S	1a	1a	1a	S	1a	1a	1a	S
POSITION DETERMINATION												
<u>Surface</u>												
Marine												
*Traffic control including collision avoidance between ships												
a. High seas	1b	1b	1b	S	1a	1a	1a	S	1a	1a	1a	S
b. Confluence areas	1b	1a	1b	O	1a	1a	1a	S	1a	1a	1a	S
c. Harbors	-	1a	-	O	-	1a	-	O	-	1a	-	O
Collision avoidance and proximity warning, independent of traffic control	-	1a	-	O	-	1a	-	O	-	1a	-	O
Long-range navigation	1a	1a	1b	S	1a	1a	1b	S	1a	1a	1a	S
Commercial fishing	1a	1a	1b	S	1a	1a	1b	S	1a	1a	1a	S
Unmanned sensors	1b	1a	1b	S	1a	1a	1b	S	1a	1a	1b	S
Search and rescue (including distress reporting)	1b	1a	1b	S	1a	1a	1a	S	1a	1a	1a	S
AMVER (Automated Merchant Vessel Reporting)*	-	2	-	O	*Combines with traffic control in these time periods.							

(Table continues on next page)

*See para. 4.3.4.

TABLE 11.4.1 (continued)

	1970 to 1975				1975 to 1982				Beyond 1982			
	T	N	E	A	T	N	E	A	T	N	E	A
Use and report reference												
Small pleasure craft (on the high seas)	1b	1b	1b	S	1a	1b	1b	S	1a	1a	1b	S
Oceanographic research and hydrographic surveying including offshore mineral exploration	1b	1a	1b	S	1a	1a	1a	S	1a	1a	1a	S
<u>Ground</u>												
Studies of animal migration	1b	1a	1b	S	1a	1a	1b	S	1a	1a	1b	S
Exploration, including mineral search	-	2	-	O	-	2	-	O	-	2	-	O
Unmanned sensors	1b	1a	1b	S	1a	1a	1b	S	1a	1a	1b	S
Automobiles	3	1b	-	O	3	1a	-	O	3	1a	-	O
<u>Aircraft</u>												
Traffic control including collision avoidance	1b	1a	1a	S	1a	1a	1a	S	1a	1a	1a	S
Collision avoidance independent of ATC	-	1a	-	O	-	1a	-	O	-	1a	-	O
En route navigation	-	1a	-	O	1a	1a	1b	S	1a	1a	1a	S
Unmanned sensors (balloons)	1b	1a	1b	S	1a	1a	1b	S	1a	1a	1b	S
Search and rescue	1b	1a	1a	S	1a	1a	1a	S	1a	1a	1a	S
Clear air turbulence detection and position determination	3	1a	-	O	3	1a	-	O	2	1a	-	O

4.3 General Statements of Requirements

4.3.1 Marine and Air Navigation

Some of the navigation techniques that are in common use had their origins in ancient times. Progress in the development of navigation was slow up to the start of the electronic age. The use of electronic aids has improved marine navigation in bad weather, and has made possible the present high density of air traffic.

Most enroute requirements for air and marine navigation are fulfilled adequately over much of the earth's surface by long-range ground-based aids such as loran, Consol, Decca and Omega. Transcontinental service for aircraft is provided in North America, Western Europe, Japan, and to a limited extent elsewhere by a network of short range electronic aids.

Doppler and inertial on-board navigation aids provide navigation and steering information for aircraft, enabling them to travel anywhere on the earth.

TRANSIT, the Navy's operational navigation satellite system, provides for high-accuracy position fixing over the entire surface of the earth, although currently the service is intermittent at any location.

With the existence of these aids, there is no compelling requirement for further development of satellite systems <u>for navigation only</u>. Moreover, a system designed primarily for traffic control will provide a useful navigation service also, if the navigation function adds virtually no cost to the implementation and operation of the traffic control function, and if the navigation service has better geographical or time coverage, higher accuracy, simpler user procedures, or lower user equipment cost than any of the existing aids.

Although satellite systems other than TRANSIT may not be required for navigation in the foreseeable future, a discussion of navigation requirements is presented here. Marine traffic densities will increase in the future, and radically different vessels will be introduced, such as the following:

1. <u>Hydrofoil Ship</u> A hydrofoil ship is a ship with a standard displacement hull which is lifted out of the water while in motion by the interaction of foils with water.

2. <u>Ground Effect Machine (GEM)</u> A ground effect machine is a ship which is lifted from the surface of the water by a cushion of air developed by the forward motion or by a down-draft fan.

3. <u>Semi-Mecaship</u> A semi-mecaship is a standard merchant ship design which has been partially mechanized.*

*Pages 138-141 of "Proposed Program for Maritime Administrative Research-Vol. II: Contributing Studies," prepared by Maritime Research Advisory Committee, National Academy of Sciences--National Research Council, Washington, D.C., 1960 under MARAD Contract No. MA--1767.

4. Mecaship A mecaship is a standard merchant ship which has been fully mechanized or automated.*

The increase in traffic, coupled with the increase in the size and speed of ships, will require more frequent and more accurate position determination in the en route phase of a voyage. At present, position fixes twice a day are sufficient. The accuracy required for navigation on the high seas in a controlled traffic situation is between 1 and 3 nautical miles. Anticipated future requirements are presented in the Table 11.7.4, "Long Distance Aids to Navigation", marine requirements affecting the design and choice of a standard system.

Commercial fishing boats represent one of the largest groups of potential users of a satellite navigation system. The current trend is to larger ships which operate in all parts of the oceans. This trend will continue in view of the increasing demand for food throughout the world. At present, fishing boats on the high seas make extensive use of Loran/Consol and Decca, where these navigation aids are available, and celestial navigation and dead reckoning in other areas. They need to return to previously-occupied areas with an accuracy of at least 0.1 nautical miles, in all weather conditions, and in all of the broad ocean areas. Only a satellite system appears likely to provide such accurate and dependable position determination to the fishing fleets. Commercial fishermen would have a strong preference for a satellite navigation system, which allows them to perform their own on-board position determinations, with no necessity for position reporting, so that they will not reveal their private information on where the fish are. The Navy's TRANSIT system could fulfill the fishermen's need, were it not for the present high cost of user equipment.

There are large numbers of marine craft in the 16- to 100-foot length categories which for various purposes routinely make trips requiring offshore navigation. Most trips are between centers of population located on mainland and islands, while a lesser number are between islands. Sailcraft transoceanic trips are becoming commonplace. Most of these craft range in value between approximately $10,000 and $200,000, about 10 percent of which is allocated to electronic and nonelectronic instrumentation used for communication and navigation. The functions of navigation and position determination must be accomplished within these cost constraints, with equipment that is easy to operate.

Small craft on the high seas cruise at speeds between 5 and 35 knots. Offshore accuracies of five miles or better will serve to avoid most hazards. Infrequent fix determination on demand, rather than at fixed intervals, would satisfy the minimum requirements. Availability of the service at all times is more important than continuity of indication.

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*Pages 138-141 of "Proposed Program for Maritime Administrative Research-Vol. II: Contributing Studies", prepared by Maritime Research Advisory Committee, National Academy of Sciences--National Research Council, Washington, D.C., 1960 under MARAD Contract No. MA--1767.

For aircraft, the position-fixing capability that could be provided by a satellite does not fulfill all the requirements for navigation. The pilot needs in addition velocity vector information, to provide steering direction. This information can be obtained indirectly from a past history of position data. It is also available from existing or proposed navigation aids, and these will continue in use. However, the technical requirements of the self-contained aids might be relaxed if "updating" information from a satellite were available. Accuracy might be improved if a combination of satellite and self-contained systems were employed.

4.3.2 Air and Marine Traffic Control

The function of an Air Traffic Control (ATC) agency is, in general, to manage the airspace assigned to it. Approval of flight plans; issuance of directions to change course, speed, or altitude; or to proceed to another destination; or to delay by flying repeatedly over a reference point, are the principal means for carrying out the function.

The basic inputs to the ATC agency are the positions of all the aircraft in the airspace. The more accurate the positions, and the more often they are received, the better the agency can carry out its function. When position reports are suspected of being in error, or are received only infrequently, the agency must resort to wide separation between aircraft in order to have a margin of safety.

Wide separation makes for inefficient use of the airspace. It prevents some aircraft from flying at the altitude or on the track or at the time they desire.

Over the continental United States, the ATC obtains positions of aircraft by radar on a continuous basis. Minimum separations are 3 to 5 miles. Over the oceans, ATC obtains on-board determinations of position. The pilot's communications are by HF radio. Because the positions may be in error, and because of the delay in receiving them, the separation minima are set at 20 minutes flight time along track and 120 nautical miles laterally, for aircraft operating at the same altitude.

These very large separations were acceptable a decade ago, when relatively few aircraft were flying across the oceans. They are still acceptable over most of the world, but traffic across the North Atlantic has increased so much that severe penalties in operating efficiency are foreseen in the near future. At peak traffic hours, many aircraft are delayed because there is no airspace available for them. Others must detour to obtain airspace.

Two years ago, a proposal to reduce the separations was opposed by the airline pilots, who claimed that within the present arrangement for control of the North Atlantic airspace, the separation between aircraft could not be reduced without sacrificing safety. Similar problems are anticipated on other high-density routes.

Over the years since men first ventured on the high seas, the captain of each vessel has been free to sail on the course and at the speed he desired.

During the last century, ship captains have been bound to observe the Rules of the Road for the Prevention of Collision at Sea, a body of regulations set by international agreement. In addition, sea lanes have been established for the separation of traffic proceeding in opposite directions across the North Atlantic Ocean, and in certain international waters close to Europe and to North America.

Avoidance of collision between ships is a matter of judgment for the captains concerned. They observe each other by visual or electronic means, anticipate each other's intentions, signal by means of whistles or VHF voice communication, and obey the Rules of the Road for determination of right-of-way. The ability to avoid collision is thus a combination of observation, judgment, and cooperation.

A traffic-control system for ships would be operated by Maritime Traffic Control agencies which would function in a manner similar to existing Air Traffic Control agencies. It would assign routes, monitor progress, resolve conflicts between vessels moving into the same sea space, and arrange for an orderly flow of traffic through confluence areas. In general, such agencies would manage the international sea spaces.

As the efficiency of marine operations increases, the penalty for delays or loss of service of a ship has an enlarged effect on the total operation. In some cases, shipping may be regarded as a part of a larger system, for example, an oil company with a fleet of tankers. Efficient operation requires close scheduling of the ships, with the fleet operating at nearly its full capacity. Should one of the ships be damaged in a collision or stranded and thus removed from service, it may be necessary to shut down the oil fields until another ship can be chartered. Losses due to closing down the operation may approach a million dollars a day, a loss that may be far higher than the damage to the vessel itself. In addition, charter costs for a substitute vessel may be much higher than the costs of operating one of the vessels in the fleet.

Many new developments are aimed toward higher efficiency in shipping. High-speed ships for containerized cargo can improve efficiency by shorter time in port and higher speed en route, so that fleets now being built will require little more than half the number of ships to handle as much cargo as fleets now in service. Very large tankers, with capacities measured in hundreds of thousands of tons, are now in service, and capacities approaching a million tons are foreseen. The loss or even the delay of such large ships has a serious economic effect. The grounding of the supertanker TORREY CANYON at Seven Stones, in March 1967, illustrates such a loss, one which was compounded by serious pollution problems.

Furthermore, there are liability problems to be considered. At the present time there is a limitation on the liability of the vessel's owner in spite of negligence of the vessel's crew during a voyage. It is argued that this is an anachronism, given present-day technology in communications and navigation aboard ship, and that the owners can be held liable without limit. A navigation and traffic control satellite system may very well help reduce the specter of higher liability in the future. There is a growing recognition that marine traffic control in certain areas can be an important means to reduce collisions and groundings, and to improve day-to-day operations.

Satellites offer the means to provide traffic control for aircraft and ships in regions where it is not practical to provide it by other means. Traffic control requires the following means whereby:

1. The director of a mobile will know its position with reference to from one to three coordinates.

2. A traffic control agency may know the position of all mobiles which come within its area of cognizance.

3. The traffic control agency may determine within a quasi-instantaneous time frame safe paths of travel for all the mobiles under its cognizance.

4. The traffic control agency may relay decisions to all the mobiles under its cognizance.

5. Several traffic control agencies may coordinate their activities.

In section 7.0 a procedure for determining requirements for air and marine traffic control is presented, including accuracies, fix rates, and communication capacities.

For aircraft absolute accuracy of position determination is less important than relative accuracy. A bias in position, such as might be caused by ionospheric propagation effects in a satellite system, is not important, since it displaces aircraft in a given area by the same amount and direction, but does not place them in a hazardous region. By contrast, absolute accuracy is important to ships, because a bias error in the location system may displace them toward fixed hazards.

4.3.3 Marine and Air Safety

The Subcommittee on Safety of Navigation of the Intergovernmental Maritime Consultative Organization has agreed to recommend that all ships of over 1600 gross tons be required to carry radar.

This same subcommittee, reacting to a continued study of questions brought to light by the loss of the TORREY CANYON, proposed as an amendment to the regulations of the 1960 International Convention for the Safety of Life at Sea, that in consideration of the grave consequences of accidents which may occur to ships carrying oil or other noxious or hazardous cargos in bulk, such ships should be required to carry an efficient electronic position-fixing device suitable for the trade in which the ship is employed. A satellite system providing traffic control in confluence areas, plus general surveillance and accurate position determination in other areas, would be a possible solution to the problem of avoiding such disasters.

The Subcommittee on Radiocommunications of the Intergovernmental Maritime Consultative Organization (IMCO), in its fourth session held in April 1968, as part of the consideration of future improvements regarding the maritime distress system, took into account the possible use of VHF and UHF radiotelephony equipment, mainly for air/sea communications. The implications of the use of satellites as a relay at these frequencies appear very favorable.

4.3.3.1 Emergency Position-Indicating Radio Beacon (EPIRB)

These are small radio beacon transmitters intended to be carried by both ships and aircraft. At the present time, international efforts in this field are being made to standardize procedures, equipment, and frequencies, perhaps in consonance with the applicable recommendations of the International Civil Aviation Organization (ICAO) and the International Radio Consultative Committee (CCIR). In the United States, the EPIRB has been designated as a Survival Craft Station, and the officially adopted frequency is 2181 kHz.

The U.S. had advocated VHF/UHF frequencies, but some countries that are not making extensive use of aircraft for search and rescue work cannot see any justification for the VHF/UHF beacon frequencies of 121.5 and 243 MHz. This type of beacon is already widely in use in Japan, where it is reported that approximately 17,000 are in use. Again, a satellite system may improve the effectiveness of such a device in the area of air and marine safety.

It has been suggested that coded beacons of this kind could be planted on icebergs and floating hulks which are navigational hazards.

4.3.3.2 Nuclear Ships

Thereis concern about the consequences of a collision involving one or more nuclear-propelled ships. The United States pioneered in the non-military aspects of nuclear propulsion, with the N.S. SAVANNAH. The Soviet Union, West Germany, and Japan have since become similarly involved. The degree of expansion in the use of this type of propulsion for the world's fleet of merchant ships is not clear at this time. However, regardless of the number of such ships, it is probable that the likelihood of collisions involving them would be considerably reduced by the advent of a navigation and control system utilizing satellites.

4.3.4 Search and Rescue

The implementation of efficient search and rescue operations requires starting with minimum delay, if the greatest probability of success is to be achieved. Thus, the positions of all aircraft and ships should be constantly monitored. Immediate communications should be possible between a control center and the vehicles involved, so that all necessary participants can be rapidly vectored to the desired position.

Accurate knowledge of the relative positions of all search craft is desired, so that efficient search patterns may be developed. This is required in view of the protracted time from the first alarm to the arrival of potential rescuers. An accurate reference position established at the last known locality of the craft in distress forms a pivot point about which an accurate and efficient search can commence.

A single search and rescue organization may be sufficient for land, sea and air requirements, and could cover crashed aircraft (whether on sea or land), marine disasters, or lost exploration parties, for example.

At the present time, the transmission of a distress message by an aircraft or a ship at sea initiates a complex search and rescue effort by combined ship/aircraft teams. Effectiveness of communications is a paramount consideration, from the initial distress message to the final rescue. The station in control of distress traffic must have a noise-resistant medium handled in a disciplined manner.

Most vessels use communications in the MF/HF bands. Each year has brought increasing congestion and interference to the 2-MHz users. Additional complications include the fact that most smaller vessels have radiotelephone installations only, whereas large ships, which have both radiotelephone and radiotelegraph, generally prefer to use the latter. Moreover, the absence of commonality of frequencies between ships and aircraft may hamper search and rescue operations. Except for specialized military aircraft primarily in the search and rescue (SAR) service most ship-and-aircraft intercommunication is now carried out via aeronautical ground stations and maritime coast stations. Commercial aircraft have largely shifted to higher frequencies. Even when ships and aircraft are both equipped with VHF radiotelephone, intercommunication is seldom possible. In addition to frequency differences, modulation differences exist; aircraft use AM and ships use FM.

In recent years it has become apparent that in many cases, and under nearly all weather conditions, the modern aircraft is the most effective search vehicle for locating survivors at sea. This is particularly the case with SAR aircraft designed and outfitted for this type of operation, and maintained in readiness at all times. The aircraft is particularly effective if the area which the survivors are thought to be in is large, and its boundaries only vaguely defined.

The Automated Merchant Vessel Reporting (AMVER) system can be effective in regions of relatively dense marine traffic. Under the AMVER system the U.S. Coast Guard receives information voluntarily radioed in by merchant vessels concerning their movements. Inputs are: positions, course, and speed. This information is fed into a computer programmed to develop and update positions. Approximately 3000 ships, of more than 60 countries, report to AMVER each day. AMVER synoptically displays potential sources of help in the event of emergencies such as serious crew illness or the possible threat to a ship's safety due to storm or fire. The present position reporting accuracy required by ships in the AMVER program is $\pm$ 5 mi. A report every 12 hours is considered satisfactory.

The present serious drawback to effective operation of AMVER is that ship position reports are not mandatory. If they were, a missed report by some specified time would alert authorities to a possible distress situation.

The lesson learned from the disappearance of the S.S. MARINE SULPHUR QUEEN* suggests that more frequent navigation communications are essential in normal ship operations so that shore stations may be alerted to possible needs for assistance.

The reporting in AMVER is presently done by MF/HF radiotelegraphy, with its serious propagation deficiencies. Messages usually get through to the AMVER center, however, although relays may be required. Under present traffic density conditions, the system works adequately with existing communications methods. Hence, for the present time frame, no satellite relay is required. Later, the increase in traffic and in size and speed of ships will require that AMVER be incorporated within an operating maritime traffic control system supported by satellites.

A satellite system can be designed for commonality of communication procedures and frequencies by ships, transoceanic aircraft, and maritime services provided by the various nations. The organizations which would play roles in the implementation of such a system would be the International Conference on the Safety of Life at Sea (SOLAS), the Intergovernmental Maritime Consultative Organization (IMCO), the International Telecommunication Union (ITU), the International Radio Consultative Committee (CCIR) and the International Civil Aviation Organization (ICAO). For the United States, the FCC and (within the Department of Transportation) the FAA, and the Coast Guard may be involved, along with commercial air and shipping organizations.

It is expected that the use of Navigation and Traffic Control Satellites will materially alleviate the problems previously described, by providing frequent position fixes and a commonality of communication frequencies.

4.3.5 Weather Advisories

The communications links afforded by satellites can improve the collection and dissemination of environmental data throughout the world. A satellite system with a position-fixing capability may aid in the collection of data by locating unattended sensors such as data collection buoys, weather balloons, and sensors aboard ships and aircraft.

The collection of weather data has long been recognized as one of the important applications for satellites. TIROS, Nimbus, and TOS have been developed for this application. One of the services provided by the satellites is Automatic Picture Transmission (APT). Over 400 ground facilities in 40 countries are equipped with modest receivers capable of recording pictures of cloud cover in their areas, as the satellite passes over.

NASA's Applications Technology Satellites, ATS-I and ATS-III, are frequently used to demonstrate the transmission of weather facsimile, WEFAX.

*The SS MARINE SULPHUR QUEEN, a large commercial chemical carrier, disappeared in 1963 while in transit between the Gulf Coast and the Northeast Coast of the United States. No trace was ever found.

APT facilities that can be tuned from their usual frequency between 136 and 137 MHz, to the ATS 135.6-MHz frequency, can receive weather maps, cloud cover pictures, and other meteorological data that can be received on a weather facsimile machine.

The prompt dissemination of weather data which are more accurate, because of satellite sensors, can contribute to the safety, comfort, and efficiency of air and marine operations. At the present time, satellites are not being fully exploited in the collection and dissemination of weather data.

Through the WMO (World Meteorological Organization) there is a vast network for collection and dissemination of weather data over most of the world. Russia, China and other communist nations participate.

Although it serves the general public, the system is of major use to aviation, in most parts of the world.

In the Northern Hemisphere there are many communication networks serving domestic and overseas areas with weather data in several forms. Some of these networks include FAA Service A, Service O and Service C, the Joint Numerical Weather Prediction System, and NAVWEPS (the Navy Numerical Weather Prediction System). Alpha-numeric, numerical, and facsimile systems are used, with automatic 12 hourly, six hourly, and specials being supplied to automatically addressed stations in the networks.

For aviation, the information is collected and studied at operations offices. The meteorologist, dispatcher, and pilot work as a team in handling information for the preparation of flight plans and later in the establishment of takeoff and immediate post-takeoff clearances.

After becoming airborne, the pilot can receive general weather broadcasts, special advisories from air traffic control, and specific forecasts regarding his flight area from the meteorologist, dispatcher, or operational control, depending upon the type of aeronautical operations involved.

In addition to general meteorological services, special services are available for reporting clear air turbulence (CAT) and other severe storm warnings in CONUS (USA) and the North Atlantic. These services should be expanded to include other parts of the world, in accordance with the provisions of Appendix 27 of the Regulations of the International Telecommunication Union (ITU). Pilot reports (PIREPS) are also received at the ATC or operations office and immediately placed in a special report category on the weather nets, as applicable.

The supersonic transport (SST) faces an as yet unassessed threat posed by radiation from solar storms. Communications must be provided for immediate dissemination of data concerning radiation storms and forecasts thereof.

The safe and effective operation of ships that ply the North Atlantic and other waters subject to seasonal storms and high winds is influenced by their ability or lack of ability to avoid potentially dangerous seas.

For marine services, weather information is broadcast periodically by both government and non-government stations utilizing frequencies provided for public or safety communications. These stations also broadcast information on hazards to marine navigation, such as floating hulks and icebergs. Hurricane, typhoon, and dangerous storm warning information is usually made available well in advance of the incidence of such conditions. Many ships participate as observing stations in the world meteorological organization, and provide twice-daily reports in a standard format.

Currently the LF/MF/HF spectrum is utilized for collection and dissemination of weather data with ships and aircraft. Generally, such communication is satisfactory. However, precipitation and thunderstorm static often renders these frequencies unusable when they are most needed, such as during the advent of hazardous weather like hurricanes at sea, and thunderstorms or line squalls (for aircraft in flight).

With the advent of noise-free, dependable communications through satellites, selected aircraft can readily become automatic weather sensor and relay terminals, thereby extending the weather sensor inputs to the meteorological system.

To date, weather facsimile and teletype-transmitted weather maps are transmitted over point-to-point circuits. However, this service is not available over ground-to-air circuits in this form. Alpha-numeric weather sequences are available on some ground-to-air circuits, with printout in the aircraft on page printers or printing-tape punches. The availability of high-grade, long-distance satellite circuits can render the general use of automatic weather printout in long-distance aircraft feasible. Such use may be a logical application of the air/ground satellite data link. Data-link studies for aeronautical services have been conducted for many years by the Radio Technical Commission for Aeronautics. Reports of Special Committees 100, 110, and 111 of the Radio Technical Commission for Aeronautics (RTCA) describe functional requirements for a short-range system which could be extended to transoceanic service, if sufficient circuits and bandwidth were available via satellite relay.

In the operation of supersonic transports, the temperature profile in the flight region where transition takes place between subsonic and supersonic speed is very critical to flight economics. If adequate sensors are available from meteorological satellites or other sources to plot the temperature profile, this information can be automatically relayed to the SST pilot for his use.

For ships, accurate knowledge of weather has always been essential to the accomplishment of a safe and comfortable voyage. Additionally, the advent of today's faster ships and the concomitant increase in competition have introduced a strong interest in the use of "least-time" or "optimum" tracks. The international weather services can be effective only if they have sufficient and reliable inputs from ships and stations strategically placed around the world. The feed back to the user is the weather map or a set of weather advisories.

A current program is coordinated by the World Meteorological Organization (an agency of the United Nations) which standardizes and prescribes the methodology employed. Present communication is primarily by MF/HF radiotelegraphy. For smaller craft, it is usually by radiotelephony. Transmission may be by Morse Code, plain language, or by facsimile. One of the newest services available is the reception of pictures directly from the weather satellities by APT (Automatic Picture Transmission).

Some ships are designated as official Weather Reporting Ships and must submit to the Weather Controls (via coastal stations) periodic readings of the weather elements at their location. All ships are recipients of weather reports and advisories. At the present time, a large proportion of the usage of HF is the transmission of weather data, with the usual drawbacks of this communication medium being present. Currently, it is not unlikely to receive a facsimile map so permeated with noise as to be unintelligible.

Savings brought about by weather routing are of substantial consequence. Corollary benefits accrue in factors such as minimization of heavy damage to ships, cargo, and personnel. In all instances, the fairly well-established benefits of a least-time-track are dependent upon timely weather services and effective communications.

4.3.5.1 Clear Air Turbulence (CAT)

Clear Air Turbulence (CAT) is defined as "atmospheric turbulence which is not visible to the naked eye and which produces uncomfortable, dangerous, or other undesirable effects, mechanically or aerodynamically, upon an aircraft or missile."*

CAT has destroyed large and small aircraft; caused fatal and non-fatal injuries to passengers and crews in planes which are not destroyed; and cost the airlines an estimated $16 million per year because of diversions to avoid wide areas where CAT encounters are reported.**, *** CAT is also of major importance in United States Air Force operations.

CAT is a potential threat to SST (Supersonic Transport) operations because the prevalence and intensity of CAT at SST altitudes has not yet been determined with certainty, and because a long-wavelength perturbation, which would disturb a subsonic aircraft only moderately, may constitute severe CAT for an aircraft traveling at supersonic speed.

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* Paul Rosenberg, "Clear Air Turbulence," (Journal of the Institute of Navigation), Vol. 13, No. 4, pages 338-342, Winter 1966-67.

** NASA Report CR-62028, Flight Safety Foundation, Contract NSR-33-026-001, December 1965, page 198.

***NASA Report CR-90041, "Clear Air Turbulence," Paul Rosenberg, Samuel P. Saint, and Jerome Lederer, March 1967.

Unfortunately, there is no proven reliable method for detecting and locating CAT sufficiently ahead of an aircraft to permit evasive action. The various methods which have been publicized so optimistically have failed to achieve a sufficiently small false-alarm rate to be useful operationally. These methods include (but have not been limited to): radar; laser radar; infrared sensors; monitoring air temperature at the aircraft; electric field measurements; ozone detection; and microbarometric measurements.

There are eight different categories or types of CAT.*

Part of the problem is that CAT is often a localized microscale phenomenon which cannot be predicted or pin-pointed from mesoscale or microscale meteorologic forecast data. Although mesoscale forecasting of CAT is improving, it is not likely ever to be able to forecast the location and time of local, microscale CAT, any more than the times and positions of individual, small, local thundershowers can be forecast with pinpoint accuracy.

Relatively little is known about the physics and meteorology of CAT, despite theories involving power spectral densities, wind shears, Richardson numbers, and Tatarski models. The fact remains that we know little about such basic parameters as the pressures, temperatures, constituents, or velocities of the air in CAT, or how much water vapor, aerosol material, or particulate matter is in the air in CAT. More observational investigation and research are sorely needed if we are to solve or alleviate the CAT problem.

In the present state of the art of CAT detection and forecast, no system can be proposed for detecting and locating the position of CAT with the aid of a satellite.

4.3.6 Operational and Management Communications

Voice communication between aircraft in flight and ground facilities operated by their companies is essential to their operations. As a result of the successful experiments using NASA's ATS-I and ATS-III satellites, the airlines have expressed strong interest in improved operational and management communications through satellites for their transoceanic craft.

There is usually a requirement for communications between a ship and its management-control or operational-control agency to assure the most economic and efficient operation of the ship. Such operational-control communications are provided by line-of-sight frequencies when ships are operating so close to the shore that land-based facilities can provide the communication. Voice communications are used at frequencies between 156 and 162 MHz.

When operating farther seaward, out of line-of-sight range of shore installations, it is necessary to utilize the MF or HF spectrum, which is

*Paul Rosenberg, "Clear Air Turbulence," (Journal of the Institute of Navigation), Vol. 13, No. 4, pages 338-342, Winter 1966-67.

subject to propagation anomalies and is thus unreliable. A satellite using line-of-sight frequencies could avoid these problems.

The technical feasibility of satellite relay of ship-to-shore communications has been demonstrated by the ATS satellites, which have provided relay of VHF from ships-to-shore locations.

4.3.7 Unattended Sensors

There are several recognized needs for communication links between unattended sensors and an intermediate or final data-collection point. These sensors include:

1. Those on moored and floating buoys, such as those of the National Data Buoys System (NDBS)

2. Beacons on floating obstructions, derelicts, icebergs, and other navigational hazards

3. Sensors on board ships at sea, for oceanographic, meteorologic and ship performance functions

4. Ground-based meteorologic, seismic, and vehicle performance functions

5. The telemetering of the condition and location of particular animals or herds

6. Balloon-borne meteorologic devices

7. Sensors on board aircraft for determining ship and pilot performance, as well as meteorologic functions, including data on jet streams and clear air turbulence

8. Beacons on survival craft, such as Emergency Position-Indicating Radio Beacon (EPIRB)

In most instances these transmissions are simple, unidirectional signals, although particular implementation may require two-way transmissions for query or command signals. Present systems are generally designed for specific functions and most frequently employ line-of-sight transmissions and digital modulation. Error-correcting coding techniques are employed where necessary.

Satellite communication links for transmission of unmanned sensor data will be used where other transmission means are not available, or where the satellite techniques present a clear economic justification as compared to other systems. In most instances the satellite will act as a simple repeater, relaying data from the sensor to the collection point. In particular implementations, the satellite will be a source of sensor data, with onboard detectors.

Satellites are especially attractive when it is necessary to locate the remote sensors as well as to collect their sensor data. Each unattended sensor may be assigned a unique address code. It may then be read out and located upon the transmission of a command transmitted by a satellite, or initiated at a ground terminal and relayed through a satellite.

4.3.8 Malfunction Warnings

It is desirable to alert a control center, for the purposes of safety and operating efficiency, when the performance of a human operator or some item of equipment (engines, instruments, structure, etc.) has degraded. The data would be telemetered via the satellite communications link to a control center, for subsequent action, such as a search and rescue operation, change in operating instructions, or standby repairs.

4.3.9 Other Applications

In addition to the aircraft and maritime applications discussed above there are other categories of users who may use a satellite system if it is put into operation and is available.

One important application is in oceanographic research, hydrographic survey, and offshore geophysical exploration. Ships involved in such operations should, in any case, be participants in the traffic control operations. However, they add a requirement for increased accuracy in the satellite system's position fixing function. Accuracies of 0.1 nm are needed, and 0.01 nm can be useful in some cases.

There is some interest in land navigation in remote areas for such users as exploration parties, trappers, miners, and geophysical prospecting. A useful application will be search and rescue in remote areas.

The use of satellites for monitoring automobile traffic on highways has been suggested. It is not considered reasonable to perform this function with satellites.

5.0 TECHNOLOGY

5.1 System Considerations

The major elements of a satellite navigation and traffic control system are:

1. Satellites
2. Ground Stations
3. Control Centers
4. Data Processing, Computing and Display
5. Communications
6. Users and Participants

5.1.1 Satellites

The number and type of satellites will be determined by considerations such as coverage, navigation technique selected, active or passive operation, communications capability, prime power source selected, on-board sensors chosen, and extent of services included.

To minimize the number of satellites in the system, preferred deployments have emphasized geostationary (22,000 mile, equatorial) orbits. To achieve full earth coverage, including the poles, orbits with non-zero inclinations must be used, since the highest latitude at which a geostationary satellite can be seen is 81°(satellite at horizon; for an elevation angle of 5°, maximum latitude is 76°).

5.1.2 Ground Stations

Under this heading are included all earth-based command, tracking, and communications facilities needed for system operation.

5.1.3 Control Centers

A system of control centers operating in an integrated and coordinated manner will be required for traffic control. The number of centers, their size, their interface with the data-processing and display subsystem, as well as other associated systems, will be a function of the total capabilities of the operating system.

Much of the experience gained over the years in Air Traffic Control (ATC) operations will be applicable to the development of a fully integrated network. Control of marine traffic has never been as formalized or sophisticated, and has only recently begun to develop along similar lines.

A well-coordinated control network must be developed with efficient displays and other operator aids; a large, rapid-access storage bank; and efficient data transmission among all system elements. The control system will be a key element in determining how well the multi-functional navigation/traffic control system meets its mission goals. Fundamental to these goals is the concept of effective service to the users. The extent of this service should be determined on the basis of cost-effectiveness since there is a large variety of conveniences which may be added. But as a minimum it may be anticipated that the services will include synoptic displays of all vehicles, potential hazards, significant meteorologic and oceanographic data, special notices and advisories, air/sea rescue and medical information, and provisions for relaying required communications. Additional services may include means for calculating optimum and alternate paths; en-route speed control; derivation of daily and weekly traffic statistics; support to scientific, oceanographic and exploration parties; and other such desirable functions.

It is not considered advisable to keep adding functions and responsibilities to the point where the integrated system becomes a monolithic oligarchy. It would appear preferable to have separate major systems which interface at the appropriate levels, a notable example being an integrated meteorological (and possible oceanographic) service.

5.1.4 Data Processing, Computing and Display

Effective operation of the system requires an efficient data processing, computing and display system upon which the control network will depend. The computers may be located at each control center, or may be further centralized, with data communication links set up among all the related components.

The computers must be capable of storing and updating:

1. Positions of all users
2. Users' status including equipment performance
3. Pertinent meteorologic and oceanographic data
4. Position of fixed and varying obstructions and hazards
5. Location of excluded areas, etc.

The equipment should be capable of filtering, discriminating, coordinating, and displaying:

1. Positions of all craft, participating and non-participating
2. Locations of all potential hazards
3. Separation distances and warnings
4. Environmental synopses

5. Search and rescue data

6. Miscellaneous data, communications, and warning

The operation requires a comprehensive and well-organized storage and retrieval system with convenient display techniques to aid the controllers. An extremely careful system study should be made to determine the number, type, and location of the computers as well as their operating characteristics, growth capability, and ancillary functions.

5.1.5 Communications

The communications subsystem will relay data, information, and commands among all elements of the system.

In contrast to the navigation or position-fixing function, the system communications requirement will be quite demanding, requiring one or two orders of magnitude more bandwidth in the satellite system, and a complex network connecting the various system participants and associated elements. To keep satellite transmitter power requirements at reasonable levels without imposing unacceptable demands on user antenna performance, it will be important to design for the most efficient flow of information, by careful selection of modulation techniques and message formats.

The number of potential aircraft, marine and other users will be such that a high degree of system discipline will be needed to minimize system access problems.

5.1.6 Users and Participants

Important considerations are the on-board user equipment requirements and interfaces with other navigation aids or on-board instruments.

Specifically, it must be recognized that a tremendous investment already exists in present aircraft and marine equipment, and users would be loathe to abandon useful equipment or invest in expensive devices for new systems. Most probably, the existing systems will be used as prime or backup techniques for a decade or more, while transitioning to satellite techniques, should they prove feasible. In addition, tradeoff analyses must be made to determine the optimum balance of user equipment size and costs to satellite (or ground-based) common system components.

Another important concern is the choice of passive versus active systems, and the impact this will have on maintaining contact with non-participating vehicles. When traffic density increases as anticipated, and separation distances are reduced to accommodate the increase, collision avoidance will be an even greater concern, and continuous surveillance must be maintained by the traffic-control operators of all vehicles whether participating or not. Similar considerations apply in air/sea rescue operations.

There will be a natural resistance on the part of commercial interests to any proposed system which requires duplication or complexity of on-board equipment. Reliability and economy of utilization of equipment are the two prime considerations for ship operators, since merchant ships generally do not carry on-board the repair capabilities called for by complex equipment. Aircraft users are concerned with weight, size, and costs.

If the satellite navigation/traffic control system contributes to the automation of navigation requirements on a ship, this will be an important factor in its general acceptance. Any increase in the number of ships and in their size and speed implies a contraction of time for decision-making on the part of the watch officer. Any function which is eliminated or reduced enhances his effectiveness in the total picture. This can be a crucial requirement when large ground effect machines (ships) doing 100 knots or more appear on the world scene.

5.2 Supporting Technology

The functions required of the system elements described above imply the need for technology to aid in making decisions in the following areas:

1. Selection of position-fixing techniques
2. Satellite tracking and station keeping
3. Selection of link frequencies
4. Selection of modulation schemes and message formats
5. Design of user equipment
6. Overall organization of the ground complex (control, data processing and communications subsystems)
7. Satellite design

It is important to note that the basic supporting technology is available now to design a satellite navigation and traffic control system which can satisfy all of the known aviation and marine requirements. Thus, a research and development program should be directed primarily towards two broad objectives: first, the optimization of candidate systems; and second, developing information and criteria for selecting a "best" system.

There is one exception to the statements made above. Navigation satellite systems have been proposed in which position-fixing is dependent on radio frequency angle measurements. It is not certain that radio frequency angle measurements can be made with sufficient accuracy; so adoption of such a system must be contingent on further research in this area. (See Section 5.2.3 below.)

5.2.1 Propagation

Relevant propagation effects can be listed under the following categories:

Atmospheric absorption

Sea reflections (multipath)

Scintillation

Faraday rotation

Propagation velocity

Refraction

Atmospheric absorption and scattering is significant only below 50 MHz (ionospheric) and above 15 GHz (tropospheric). Heavy rainfall can cause occasional problems above 5 GHz. These phenomena effectively eliminate the use of optical and infrared devices, which are most seriously affected during bad weather just when navigation and traffic control are most needed.

Sea reflection and multipath must be accounted for at lower elevation angles. Although reflection coefficients vary somewhat with sea state, frequency (being somewhat more favorable at the higher frequencies), and polarization, appropriate shaping of the user's antenna pattern is probably the most effective means for suppressing the reflected wave.

Because the range difference between direct and reflected wave is proportional to the altitude of the user's antenna, this problem can be important in aircraft applications, but should not be of serious concern to marine users.

Scintillation should not be a serious problem above 300 MHz, nor in the 100-300 MHz band over most of the globe. However, it should be noted that most of the available data were obtained during a period of low solar activity. Existing NASA ionospheric programs are now accumulating data in this area.

Faraday rotation of plane-polarized radio waves traversing the ionosphere can result in severe fading at all frequencies of interest, arguing strongly for the use of circular polarization. It is important to note that although the total Faraday rotation angle decreases with increasing frequency, frequencies above 3 GHz are needed to assure maximum rotation angles of less than 90°.

Propagation velocity uncertainties can cause significant errors in range measurements. However, although it is not possible accurately to predict ionospheric conditions for some specific epoch, the statistical properties of the ionosphere are now known well enough so that it is possible to select a frequency to reduce the maximum expected error from this source to a specified level (since this effect is inversely proportional to frequency squared).

To indicate the magnitude of this effect, the (uncorrected) range error at 120 MHz for a moderately disturbed ionosphere can exceed 5 km at low elevation angles. At 1600 MHz, this error is smaller by a factor of $(120/1600)^2$, or about 30 meters. This clearly argues for the use of higher frequencies, particularly in marine applications, where the use of VHF would provide marginally useful accuracies at best. The influence of the troposphere on propagation is relatively modest, and is independent of frequency below 10 GHz. In most cases it can be ignored; but quite simple corrections can be used to reduce the total tropospheric range error from a maximum of about 30 meters at 5° elevation angle to less than 10 meters.

NASA's GEOS-II spacecraft can provide definitive experimental data on propagation effects on ranging accuracies. This satellite carries an array of optical corner reflectors for laser ranging, plus radio ranging transponders at 400 MHz (Sequential Correlation of Range -- SECOR), S-band and C-band. It is possible to obtain simultaneous range measurements for direct comparisons of the radio system with the laser results, the latter being accurate to 5 meters or better.

Refraction is used here in the narrow sense of the word, i.e., bending of the apparent optical path of a radio wave. This phenomenon is of little consequence for range measurements at frequencies above 120 MHz, but its influence on angle measurements can be serious. Refraction results from the structure of the ionosphere. Most of the available data concern the total electron content, so that information on ionospheric structure is incomplete. A potential source of refraction data is the large body of NASA Minitrack interferometer measurements which has been accumulated for satellites such as GEOS-I and GEOS-II, for which accurate optical and doppler ephemerides are available.

5.2.2 Design of User Antennas

This is a critical design area which will interact strongly with the overall system, particularly with respect to the choice of operating frequencies, radio frequency power requirements and modulation format.

To reduce the radio frequency power required for the satellite-to-navigation link, the antenna aperture must be as large as possible without introducing the awkward need for steering the antenna -- arguing for use of the lowest possible frequencies.

The multipath problem suggests that higher frequencies should be used, because it is more difficult to shape antenna patterns to suppress reflected waves at lower frequencies. This consideration is most critical in aircraft applications, where the constraints imposed by aerodynamics and physical size and location limitations will make it difficult to control antenna patterns.

5.2.3 Radio Angle Measuring Techniques

In spite of doubt that radio frequency angle measurements can be made to the required accuracy (better than 10 seconds of arc), the potential advantages of a system based on this principle are important enough to suggest that this technique should be pursued by NASA as a long-term project. The design and implementation of an operational navigation and traffic control system should not wait for the successful development of radio angle measurements, because success may be a long time in coming. However, it is appropriate that NASA support this investigation of radio angle-measuring techniques because of its long-range potential.

5.2.4 Satellite Antenna Design

This is critical in an angle-measuring technique where both electrical and mechanical design must be done with meticulous care to meet the demanding stability requirements on the beam pattern. In general, antenna design is important for conserving satellite power, and the possibility of using electronically-steered phased arrays should not be overlooked.

Lower frequencies are desirable for up-links to the satellite, to provide larger apertures without a need for (satellite) antenna pointing. On the other hand, higher frequencies are preferred for down-links, because the antenna pattern can be more easily controlled with physically small structures, and there is no concern for aperture with respect to transmission.

5.2.5 System Design

The following development areas are fundamental to system design, but are dominated by factors which are not strictly technological, such as the choice of user base and the specific kind of service provided to each user:

1. Optimization of modulation scheme and message format
2. Multiple access provisions and application of queuing theory
3. Human engineering of user displays
4. Ground terminal organization

General studies in these areas, such as modelling of either parts of or complete systems to display the influence on the system of competing modulation schemes etc., can and should be conducted in advance of an explicit definition of system requirements. System analyses of this kind should include an examination of how collision avoidance and search and rescue operations might best be incorporated into the system.

5.2.6 Experimental Demonstration or Comparison of Candidate Systems

This will be the focal point of NASA's program. It is an effort which must necessarily be preceded by a definition of system requirements generated in cooperation with the operating agency or agencies. Only after the requirements are specified can the criteria be established for designing and properly evaluating a demonstration.

It is important that such experiments include as many as possible of the functional elements of the contemplated system, such as ground tracking and terminal equipment, navigation sets for various users, etc., as well as the spacecraft subsystem.

6.0 STATUS OF RELEVANT PROGRAMS

Design of Navigation and Traffic Control Satellite Systems will depend heavily upon experience with existing systems, the results of space experiments in progress or planned, and the study programs of various potential operating agencies and user groups.

6.1 Existing Systems

6.1.1 Ground-Based and Self-Contained Electronic Aids

1. Consol: Medium to long distance azimuthal system operating at approximately 300 kHz. Phased transmissions and characteristic dot-dash count provide line-of-position information mainly in an aural mode. Generally considered to be medium-to-low accuracy method. The coverage area is Europe and the eastern North Atlantic.
2. Consolan: Similar to Consol with modified transmitting antenna array. Operates near 200 kHz. Coverage is the ocean areas bordering the East and West Coasts of the U.S.
3. Loran A: A medium-accuracy long distance aid operating near 2 MHz. Involves envelope match of synchronized pulses transmitted from pairs of stations. The configuration of the line-of-position is hyperbolic. The system is widely implemented in the Northern Hemisphere.
4. Loran C: A high accuracy medium-to-long distance hyperbolic system using cycle phase measurement and operating at 100 kHz. If used solely as an envelope match system, it then falls into the medium accuracy category. The system is widely implemented in the Northern Hemisphere.
5. Loran D: A short baseline relatively short distance adaptation of techniques similar to those of Loran C. Highly accurate; portable when necessary. Coverage available in the S. E. Asia area.
6. Decca: Continuous wave, short to medium distance, highly accurate, hyperbolic system operating between 70 and 130 kHz. Line-of-position information derived from phase measurement; cyclic ambiguity resolved by a multiple frequency technique. The system has coverage in Western Europe, approaches to the St. Lawrence, N. E. Coast of the U.S., the Persian Gulf, certain coastal areas of India.

7. Dectra: An adaptation of Decca techniques to a long distance hyperbolic system. Coverage has been indicated to be in the North Atlantic region between Great Britain and Canada.

8. Omega: A long baseline, long distance, VLF (near 13 kHz) hyperbolic system. Line-of-position determination is by phase comparison; cyclic ambiguity is resolved by multiple frequency technique. Not fully operational at the present time; under continuing development. It has been proposed that eight transmitters will provide global coverage. Considered to be a medium-to-low accuracy system. The coverage is wide across the North Atlantic, North America, and eastern North Pacific.

9. Radio beacon - Radio direction finder: Low-to-medium accuracy azimuthal system. Required equipment on most ocean-going merchant ships. Wide coastal coverage throughout the world. A short to medium range system.

10. Inertial: A dead reckoning aid using gyros and accelerometers and measuring accelerations relative to space coordinates which are translated by integration to distance information.

11. Doppler radar: Uses the doppler effect of the reflected energy of two or more radio beams from the aircraft to provide a dead reckoning aid to determine speed and direction of the aircraft over the reflecting surface.

12. Acoustic doppler: Identical to doppler radar but utilizing acoustic beams and used by waterborne craft.

6.1.2 Conventional Methods of Navigation

1. Dead reckoning - Applying heading and speed information to last position to arrive at a new deduced position.

2. Celestial navigation - Determination of the position of the craft by the technique of accurately-timed observations of celestial bodies using a sextant. Line-of-position determined by comparison of observed and computed data based on short tabular methods coupled with ephemeris information. Influenced by conditions of cloud cover.

3. Piloting - Position determination by reference to visual bearings of buoys, lightvessels, fixed ground-based aids, prominent landmarks, and underwater soundings. Limited to line-of-sight in coastal areas.

6.1.3 TRANSIT

TRANSIT is at present the only existing operational satellite navigational system. There are now four operating satellites in 600 nm altitude circular polar orbits. Both tracking and navigation are accomplished by measuring the doppler shifts of 150-MHz and 400-MHz transmissions which are broadcast continuously. Each satellite transmits its own ephemeris and timing signals on both carriers.

The system provides full global coverage and is all-weather. Fix accuracies on board ship routinely exceed the marine requirements listed earlier. The user antenna is a single vertical whip with a ground plane.

User equipment now in use is fairly expensive (about $45,000 with computer), but a reduction by an estimated factor of 2 to 3 would result from increased production (~1000 sets). A substantial reduction in cost could be attained for users with lower accuracy requirements (1 nm) using a greatly simplified measuring and calculating procedure which removes the need for a computer. This procedure has been designed and tested, but no hardware has been produced.

Although TRANSIT is usually termed a navigation system, it is more accurate to call it a position-fixing system. It provides very accurate position fixes at discrete epochs, typically a defined point in time within a satellite pass. It has also been demonstrated experimentally that a ship's velocity can be obtained from the doppler measurements simultaneously with position.

The TRANSIT system cannot use geostationary orbits which have no satellite-generated doppler shift. Although altitudes considerably higher than 600 nm can be used in principle, best results (shorter passes, larger doppler shift) are obtained with orbits below 1000 nm.

In assessing the potential role of TRANSIT in such a system it is necessary to consider the basic fact that surveillance and traffic control demand continuous access to en route users. Because a geostationary orbit quite naturally provides such access, it is strongly preferred over the lower altitude orbits used in TRANSIT. Two added difficulties are the length of time needed to collect data for a fix (several minutes) and the waiting time between fixes, which can be quite serious for high performance aircraft using the present constellation (average waiting time about 80 minutes).

Nevertheless, there are many users who, for reasons of accuracy, or of reluctance to report their positions, might logically use TRANSIT for position fixing.

6.2 Space Experiments

6.2.1 IRLS (Interrogation, Recording and Location System)

The IRLS technique which is planned for test aboard a NIMBUS spacecraft involves the use of a ranging waveform integrated with the data-signalling wave form in collecting data from remote sensor platforms. The range and sensor data are stored in the satellite for later retransmission. The basic principle of operation may prove useful in real-time position determination and data collection, by relay through geostationary orbit satellites.

6.2.2 OPLE (Omega Platform Location Experiment)

The OPLE system principle uses the satellite as a communications link to forward raw Omega navigation data to a land station for processing. The fix accuracies are limited to the accuracies achievable using the Omega VLF navigation system. The advantage of the approach is the potential low cost and simplicity of the user terminal.

Because of its long integration and slow cycling times, Omega is more suitable for craft operating at low speeds, such as sea and land craft, than it is for aircraft. Current installation plans for aircraft include not only the Omega receiver, but also a self-contained rate sensor (inertial or doppler) to assure that the aircraft does not outmaneuver or create excessive errors in the Omega readings.

6.2.3 Communications and Ranging Tests with ATS-I and ATS-III

The ATS-I satellite provided the first opportunity for valuable experimentation with satellite relay of VHF ship-to-shore and air-to-ground communication.

The ATS-III, launched in the fall of 1967, carries a similar but somewhat improved VHF repeater experiment. These experiments have already provided meaningful data for the design of operational systems using this frequency band. The availability of both satellites provides unique opportunity for tests of multiple satellite position determination techniques.

Both the ATS-I and the ATS-III provide a bandwidth of 90 kHz. This bandwidth is more than adequate to permit ranging tests to be conducted between the ground and airborne (or shipborne) terminals. The use of ranging as a method of position determination will be tested shortly. A determination of achievable accuracies using the VHF band will be a vital experimental result for future planning of operational systems.

6.2.4 EOLE

This program involves the use of range-rate measurements on a path between instrumented balloons and a satellite. It will provide valuable data on the practical problems in designing equipment for transmitting to satellites from unmanned platforms in extraordinarily severe operating environments.

6.2.5 DOD UHF Experiments

Recent tests by the Department of Defense (DOD) using the Lincoln Experimental Satellite (LES) series have demonstrated the feasibility of satellite data transmission links to aircraft using relatively simple radio equipment and moderately sophisticated modulation techniques. The Milcomsat program involving a 1969 launch of a satellite with a hundredfold increase in output over the LES should demonstrate a practical system for multiple access by a large number and varied class of mobile user terminals.

6.2.6 Program 621B

Program 621B is a U.S. Air Force-sponsored development for provision of a precision navigation capability. The proposed system would employ 16 satellites in four constellations, each satellite weighing about 250 pounds. This deployment covers the entire globe, except for 600 mile caps around each pole.

At the aircraft an on-board computer with 4000-word storage capability is used to calculate range difference, resulting in an anticipated position accuracy of 200 to 600 feet. Operation at L band is anticipated.

The system would employ both master and slave stations to determine the position of each satellite. The stations are also required to trigger each satellite during normal operation.

The 621B program is now in its concept formulation phase, and performance specifications are being developed. Various user terminals are being considered, from manpack to full aircraft installations. While it is recognized that military systems often find civil applications (e.g., loran), the 621B program is not considered further in this study; although a high accuracy system, it is passive and therefore not suitable for traffic control.

6.2.7 GEOS

This is an existing NASA program in satellite geodesy. In view of their geodetic functions, the two satellites that were orbited under this program, GEOS-I and GEOS-II, were provided with very precise position-determining instrumentation. One of the defined objectives of the program is to obtain the best possible comparisons of the accuracies of various geodetic instruments. One of the on-board devices is an array of quartz corner-reflectors for optical laser range measurements. The results show an r.m.s. noise level of 1.5 meters, and an estimated accuracy of 5 meters. Both satellites were equipped with ranging transponders at 400 MHz (SECOR) and 2.0-GHz (Goddard Range/Range Rate), and GEOS-II has in addition a 5.0-GHz pulse radar transponder. Considerable care was taken to accurately calibrate the internal transponder delays (uncertainties are of the order of 10 nanoseconds), so accurate comparisons of ranging errors at frequencies of interest to the navigation system can be obtained by direct comparison with the laser measurements.

Preliminary results of such comparisons indicate that both the 2-GHz and 5-GHz systems can measure range to better than 25 meters. (These experiments use fixed ground terminals only.)

Both satellites carried a minitrack beacon which was used for housekeeping purposes. This may provide data relevant to the accuracy of radio angle measurements.

GEOS-I is no longer operating. GEOS-II is in orbit and now working. A third (GEOS-III) is being planned for possible launch in late 1970.

6.3 User Activities

6.3.1 RTCM (Radio Technical Commission for Marine Services)

This cooperative association of United States Government-Industry marine telecommunications agencies is conducting a review and study of user requirements through its Special Committee 60 (SC-60), "Electronic Aids to Navigation." This committee was instituted to assist the U.S. Coast Guard in its efforts in the Department of Transportation's objective of formulating a National Plan for Navigation. In its studies, SC-60 is carefully scrutinizing satellite systems.

6.3.2 AMMI (American Merchant Marine Institute)

This group, representing major U.S. flag steamship companies, is making a study of its user group requirements and providing an input in the general effort of formulating a National Plan for Navigation. The Navy navigation satellite system and proposed nonmilitary satellite systems are among the review items of this study.

6.3.3 AEEC SATCOM

A special subcommittee of the Airline Electronics Engineering Committee has been developing system design criteria and equipment standards for VHF terminals to be installed by airlines using a VHF satellite communications system. This work has resulted in a definitive design standard including installation plans.

6.3.4 RTCA (Radio Technical Commission for Aeronautics)

This cooperative association of U. S. industry and U. S. Government agencies has made eminent studies of the problems of air navigation and traffic control, such as the Special Committee 31 formed 20 years ago. RTCA continues to contribute significantly in these areas. One of the most recent of RTCA's projects is the program of its Special Committee 117, formed to develop requirements and specifications for a new aircraft approach and landing system.

6.4 International Activities

6.4.1 UN (United Nations)

On 3 August 1967, the Working Group on a Navigation Services Satellite System, of the Committee on the Peaceful Uses of Outer Space, submitted its report. The report considered the following:

1. Present concepts of potentials of a navigation services satellite system
2. Consideration of the need of a navigation services satellite system
3. Technical feasibility of a navigational services satellite system
4. Implementation

The Working Group did not recognize the need for presenting specific recommendations at that time. It is understood this topic is being handled as a continuing study by this group.

6.4.2 ICAO (International Civil Aviation Organization)

The ICAO Com/Ops Division meeting which took place in the fall of 1966 considered the potential application of satellite technology to the requirements of civil aviation. In the report of the meeting, several recommendations were made regarding specific additional studies and experiments required in the evaluation of such potential. Recently, a special panel of experts provided by certain member states has been formed to consider the various proposed space applications in detail. The work of this panel is expected to commence by late 1968 or early 1969.

6.4.3 ITU (International Telecommunications Union)

In its principal function involving the allocation of the radio frequency spectrum, the ITU has provided for bands to be used by satellite services either on a shared basis with other services or on an exclusive basis. Within the next 2 or 3 years a second World Administrative Radio Conference will be held to consider additional needs of space systems.

6.4.4 CCIR (International Radio Consultative Committee)

With its aims of studying radio and operating questions relating specifically to radio communications and issuing recommendations on them, the CCIR has study groups with many activities, including: space systems; propagation including the earth and the troposphere; ionospheric propagation; and mobile services. Since 1957 the CCIR has been investigating the unique technical problems of telecommunication with and between points in space, with special concern for questions of frequency spectrum sharing. Its recommendations are generally adhered to by ITU member states.

6.4.5 IMCO (Intergovernmental Maritime Consultative Organization)

Among its aims, it provides the machinery for cooperation among governments in the field of governmental regulations and practices relating to technical matters such as those concerning safety at sea. Its Subcommittee on Radiocommunications is presently making a study of the marine operational requirements for a safety and navigational radio system via satellites. Concurrently, its Subcommittee on Safety of Navigation is conducting studies on the requirements for a navigation service satellite system.

6.5 U.S. Government Activities

6.5.1 JNSC (Joint Navigation Satellite Committee)

An ad hoc committee was formed on September 10, 1964, by agreement of the Treasury Department, Department of Defense, Department of the Interior, Department of Commerce, Federal Aviation Agency, and the National Aeronautics and Space Administration. The Committee was directed to investigate the need for a satellite system for air-sea navigation, traffic control, emergency and rescue operations, and related functions. A major recommendation was: "A system utilizing satellites combining communications, air traffic control surveillance, and navigation functions, either separately or in combination with nonsatellite techniques, should be investigated further."

6.5.2 IGIA (Interagency Group for International Aviation)

The IGIA has accepted the task of formulating national policy and plans with respect to Aeronautical Telecommunications services using satellites. A special government-industry working committee has already begun the task of drafting U.S. planning.

6.5.3 DOT (Department of Transportation)

A National Plan for Navigation is presently being developed under the authority of the Department of Transportation. It recognizes the need for a clear, authoritative, comprehensive national policy and plan relating to navigation in order to avoid unnecessary proliferation of systems.

The Department of Defense is participating in this activity. The plan will include operational aspects, R&D, a statement of national requirements, action required to implement them, the method of financing a navigation system with considerations of user charges, assignment of responsibility, and a national policy statement. It is expected that the plan will form the basis of the United States position in international negotiations regarding navigation. The plan, which will be updated annually, is meant to reflect the needs of all user groups as well as planning groups.

6.6 Nongovernmental Activities

A considerable segment of the aviation, marine, navigation, communications and electronic industries is actively engaged in studying the problems covered in this report, and in developing applicable technologies. The companies thus engaged are too numerous to be listed here.

In addition, a number of technical and engineering societies in this country and abroad are active in the fields of navigation and traffic control through the media of technical publications, technical meetings and symposia, and technical committees. Prominent among these societies in the U.S. are:

1. The Institute of Navigation

2. The Institute of Electrical and Electronics Engineers
3. The American Institute of Aeronautics and Astronautics

6.7 Status Summary

As described above, considerable progress has already taken place in activities which could lead to world-wide implementation of satellite systems for navigation and traffic control. The feasibility of using satellite techniques to satisfy at least some of the identified future needs is manifest. The precise characteristics of future systems cannot now be defined due to the need for additional development, analysis coordination, and space experimentation. Nonetheless, the number of promising system design concepts is quite limited, and they share substantially common requirements for technology development. For this reason it should be possible to bring any system to fruition with a highly-efficient and clearly directed research and development program.

7.0 TYPICAL SYSTEMS

7.1 Determination of Requirements

Prior to development of the system models discussed in Section 7.3, the Panel considered pertinent system operating characteristics. These included: accuracy; fix rate; capacity; geographical coverage; availability; easy retrofit to existing craft; easy, infrequent adjustment and maintenance; no significant increase in on-board workload; compatibility with earth-based ATC and communication systems; evolutionary system development; efficient spectrum usage; contribution to profitability; and preference for a common channel for air and marine search and rescue.

7.1.1 Aircraft Accuracy and Fix-Rate Requirements

Traffic control requires independent surveillance of user craft positions, a decision-making agency, and undelayed communication between the agency and the craft that are enroute. The following discussion indicates a rationale for the establishment of accuracy specifications for a traffic control system based upon an analysis of current operating procedures. Although the principles are similar, the use of satellites for air and marine traffic control is considered separately in the presentation.

It is current practice for transoceanic aircraft to fly according to approved flight plans along tracks which are separated laterally by 120 nautical miles, with 20 minutes flight time separation along tracks, and vertical separation of 2000 feet between 29,000 and 41,000 feet. Each pilot is responsible for his own navigation. On-board navigation aids such as loran, Consol, Decca inertial and doppler navigators are used, with an occasional radar check by a weather ship. Each aircraft reports its position, usually as it crosses each 10 degrees of longitude. In this open-loop system, there are occasional gross navigation or "blunder" errors in which an aircraft is displaced far from its track.

It has been estimated that aircraft are displaced laterally by more than 60 miles approximately 0.05 percent of the time, or about 0.025 percent of the time on either side of the track. When all of the position displacement probabilities are considered for present-day traffic loads, the 120-nautical mile separation of the tracks affords a very high level of safety. It is considered dangerous to reduce this spacing without an independent means of monitoring the position of the aircraft.

With such independent monitoring (surveillance), an improved (closed-loop) traffic control system can be implemented which will permit reduction of track separations. One feasible system would include a pair of VHF communication satellites to relay range interrogation and thus provide the necessary surveillance, used together with communications through the satellites. The use of the system for reducing separations is illustrated in Figure 11.7.1. If the track separations are reduced to 90 nautical miles, the halfway line is separated from each track by 45 nautical miles. Within the 45-mile limit, a deviation limit is established, closer to the track than the halfway line by a distance determined from the characteristics of the surveillance system. If the surveillance system has a one-sigma accuracy* of 4.5 nautical miles, and if the deviation limit is established at 6 miles in from the halfway line (that is, 39 miles from the track), and if readings of the position of each aircraft are made every 5 minutes, 10 percent of the surveillance errors will occur beyond the 45-mile line. The product of the probabilities of the surveillance system error and the navigation system error is then 0.025 percent beyond 45 miles.

Aircraft in the controlled space will proceed in accordance with approved flight plans using their on-board navigation aids, as they do now. A craft will be warned when the independent surveillance system indicates that it has reached the deviation limit. Two things must occur before a craft will be displaced more than 45 miles from its track. First, the on-board navigation must be that much in error. Statistically this is a low probability. Second, the surveillance system must also be in error by more than 6 miles. This is a 10 percent probability (based upon the assumptions in the example under discussion). Further reductions in track separation can be achieved with the assumed surveillance accuracy.

It is expected that the communication load for traffic control over the oceans would be small. On the average, it would be less than one message per crossing to warn aircraft that they have deviated from their tracks out to the deviation limit.

Studies and experiments are now in progress to determine if the required accuracies can be met using VHF frequencies. It is estimated that plus or minus 3 to 5 nautical miles, one-sigma position-fix accuracy on the principal transoceanic routes, can be achieved in the presently used VHF band, 118-136 MHz. However, the largest error contribution (i.e., ionospheric range error) is a systematic and equal bias error for adjacent aircraft. Hence the effective accuracy will be better than shown, which may permit reduction of separation to 60 nm.

As satellite systems for transoceanic traffic control are studied and developed, consideration should be given to extending their use to continental air traffic control. Ever-increasing air traffic places a heavy burden on the present system. Individual traffic controllers are assigned sectors in which the peak traffic does not exceed the controller's human capacity. As traffic increases, the size of the sectors must decrease. This introduces problems of equipment replication, hand-over problems between sectors, high costs,

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*A one-sigma (1σ) accuracy value corresponds to a one standard-deviation of the measurements. This is a standard statistical measure of dispersion and is computed as the root mean square (r.m.s.) value of the deviations of a group of measurements about their mean value.

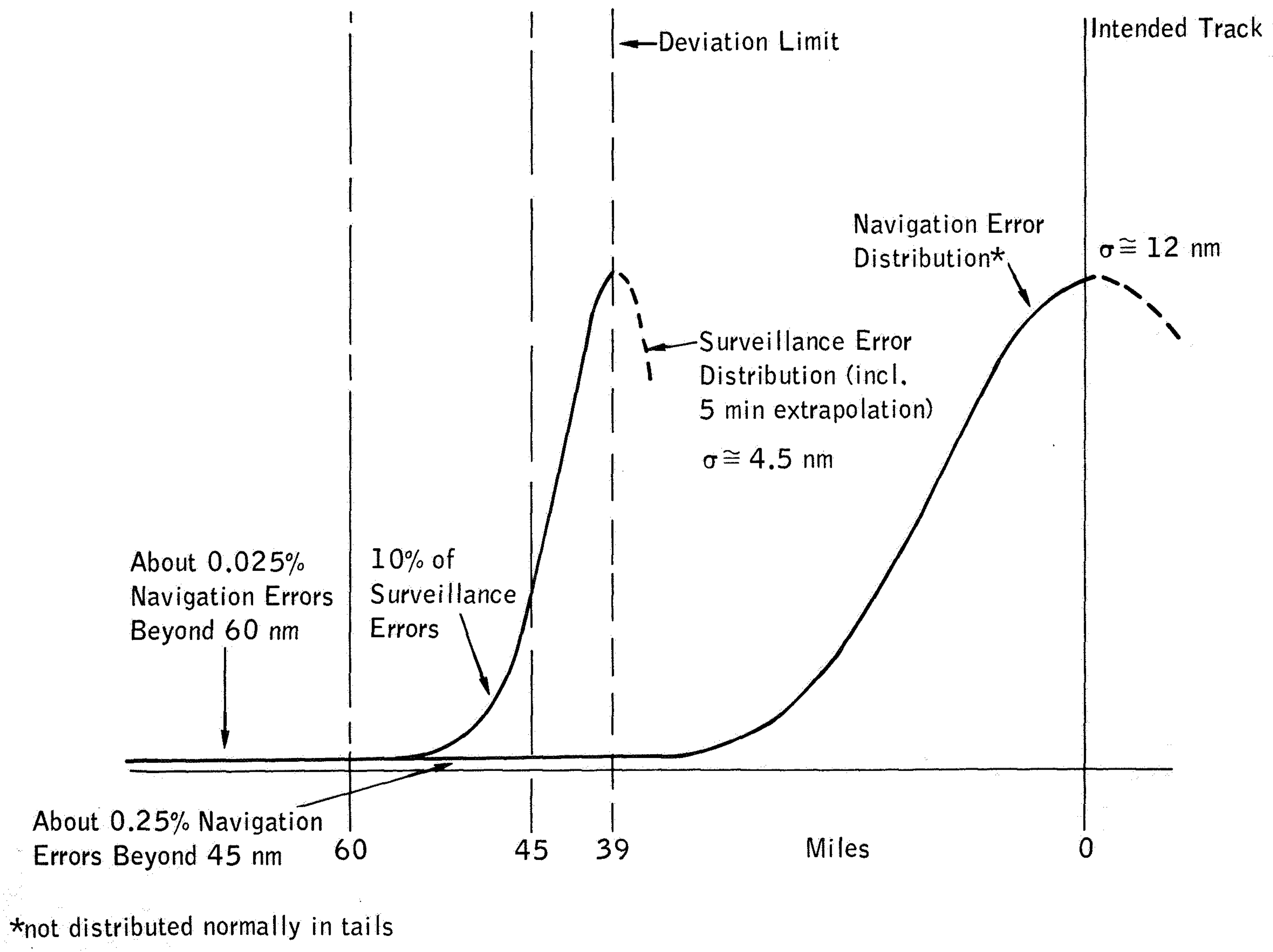


FIGURE 11.7.1 Independent surveillance system.

and, perhaps most important of all, a chronic shortage of highly skilled and trained persons who can fulfill this important function.

During a peak minute, 10, 000 aircraft are in the sky over the United States. Of these, 2, 000 may be on instrument flight rules, and therefore under air traffic control. The number is expected to triple by 1985. Accordingly, the Federal Aviation Agency is developing and installing a first implementation of a computer-controlled enroute system. Aircraft are tracked by rho-theta radar sensors, the data communicated by land lines to a central computer where it is processed, and the decisions communicated by land lines to radio transmitters within line-of-sight to the aircraft, and thence by radio to the craft.

Station spacings are 80 nautical miles along the airways. The airways are 8 nm wide. Specified system accuracy is $\pm$ 4.5°, two sigma, enabling the 8 nm airways to be maintained out to $\pm$ 51 nm from the sensors. If it is necessary to extend an airway farther, it is widened. System accuracy is defined as the root-sum-square of the ground station, airborne equipment and pilotage accuracies.

Eventually a satellite system might fulfill the sensing requirement, and substantially reduce or eliminate the need for land-line communications. In the future it may be less expensive to provide further expansion of the system by satellite than by adding to the present ground-based system. An advantage might also accrue from use of a single system for oceanic and continental air route traffic control.

7.1.2 Maritime Accuracy and Fix-Rate Requirements

As the number, speed, and variety of ocean-going vessels increases, it is becoming necessary to control their routes in order to reduce the number of collisions and strandings. The Intergovernmental Maritime Consultative Organization (IMCO) and the U. S. Coast Guard have established recommended shipping lanes for certain confluence areas of the oceans. In the Atlantic, there are confluence areas in the English Channel, the approach to the Mediterranean, the general Mediterranean area, the North Sea area, the approaches to the northeastern United States, and the United States Gulf Coast. Shipping lanes in the outer confluence areas are typically 5 nautical miles wide and the lanes are separated by a buffer zone 3 miles wide. In the inner confluence areas, the lane widths are typically 3 nm tapering to 1 nm and are separated by a buffer zone 2 nm wide. The inner confluence area leads to the precautionary area in the vicinity of the harbor.

On the average there are approximately 250 ships underway in each of the six Atlantic confluence areas, for a total of 1500 ships. In addition to these, it is is estimated that there are 3000 to 5000 ships on the Atlantic deep sea simultaneously. The total number of ships that could use marine traffic control advantageously is approximately 18, 000*, so that a marine traffic control system should be designed to accommodate that number of addresses.

*This number could reach 100, 000 if we include all private, special-purpose and fishing craft.

The problem of safe passage on the seas is complicated by the variety of ship characteristics. By 1980 it is expected that there will be surface-effect machines traveling at speeds of up to 90 knots in the same waters with 15-knot giant bulk carriers and submerged barges.

The principles of marine traffic control are similar to those of air traffic control. The vessel attempts to remain in the assigned lane by the use of on-board navigation aids. It is under independent surveillance by the marine traffic control agency. When the agency determines that the ship has deviated to the edge of the buffer zone, it is advised by the control agency how it must steer to remain within the lane.

These principles may be applied to derive an estimate of the surveillance accuracy needed for marine traffic control. Table 11.7.1 lists the presently-used navigation methods for inner and outer confluence areas near the United States and Europe, as well as on deep water, and presents estimates of the percentage of the total number of lines of position taken in each area by each method. These estimates are used to derive a statistical estimate of the position-fix accuracies achieved in each of the regions. We note that the position-fix accuracy is worse in the outer confluence area than in the inner confluence area, whereas the lane widths are not substantially wider in the outer confluence areas. This seems consistent with the observation that the outer confluence area is at the present time the most dangerous from the standpoint of large ship collisions.

Figures 11.7.2 and 11.7.3 present the use of a surveillance system in the outer confluence area shipping lanes. Plots of the estimated one-sigma navigation accuracy are shown as the solid line curves. The dashed line curves show the error probabilities for a marine traffic control surveillance system having a 0.5-nautical mile, one-sigma surveillance accuracy. Two things must occur before the ship is deviated beyond the center line of the buffer zone without its deviation being detected. Its own on-board navigation must be that much in error, and the surveillance system must fail to detect the error. Figures 11.7.2 and 11.7.3 suggest that the probability of a ship being beyond the center line of the buffer zone is very low when a surveillance system with a 0.5-nm, one-sigma accuracy is used in the presently assigned sea lanes with the presently-used navigation methods.

The required fix rate for controlling marine traffic may be estimated from steering accuracy and speed. Typical values for ship steering accuracy (interpreted here to mean the ability of a vessel to remain on an intended course) are ± 1 degree in good weather to ± 5 degrees in very bad weather. With 1 degree steering, a ship will travel approximately 90 miles to get off its track by 1.5 nm, and with $\pm$ 5 degrees steering it will travel 18 miles to get off its track by 1.5 nm. Table 11.7.2 presents the time required for a ship to deviate from the center of the track to the edge of the buffer zone in an inner confluence area. A similar estimate is made for the outer confluence area, where the lane width is 2.5 nm, and the results are summarized in Table 11.7.3. In each case, we may assume that a fix must be taken on each ship at least twice during the time that is required for a ship to deviate from the center to the edge of the lane. Figure 11.7.4 presents the maximum interval between fixes, assuming that the time between

TABLE 11.7.1

UTILIZATION ESTIMATES OF NAVIGATION METHODS EMPLOYED BY MERCHANT SHIPS IN THE NORTH ATLANTIC

Navigation Method	Average Fix Accuracy nautical miles	Percentage of Observation				
		Confluence Areas				High Seas
		United States		Europe		
		outer	inner	outer	inner	
Loran A	0.5	30	30	15	15	30
Decca	0.1	5	5	20	20	5
Consol	2.0			10	10	5
Radar (in fog)	0.1		40		30	
Visual Piloting (in clear weather)	0.1		40		30	
Soundings	3.0	10	10	10	10	
RDF	2.0	20	10	10	10	5
Dead Reckoning	5.0	20		20		20
Celestial	3.0	10		10		30
Loran C (envelope matching)	0.5	4	4	4	4	4
Loran C (phase matching)	0.1	1	1	1	1	1
	Total	100	100	100	100	100
*Weighted average position-fix, in nautical miles =		2.2	0.7	2.1	0.85	2.3

*The weighted average position-fix accuracy is obtained by summing the products of the average fix accuracies for each navigation method and the corresponding observational percentages.

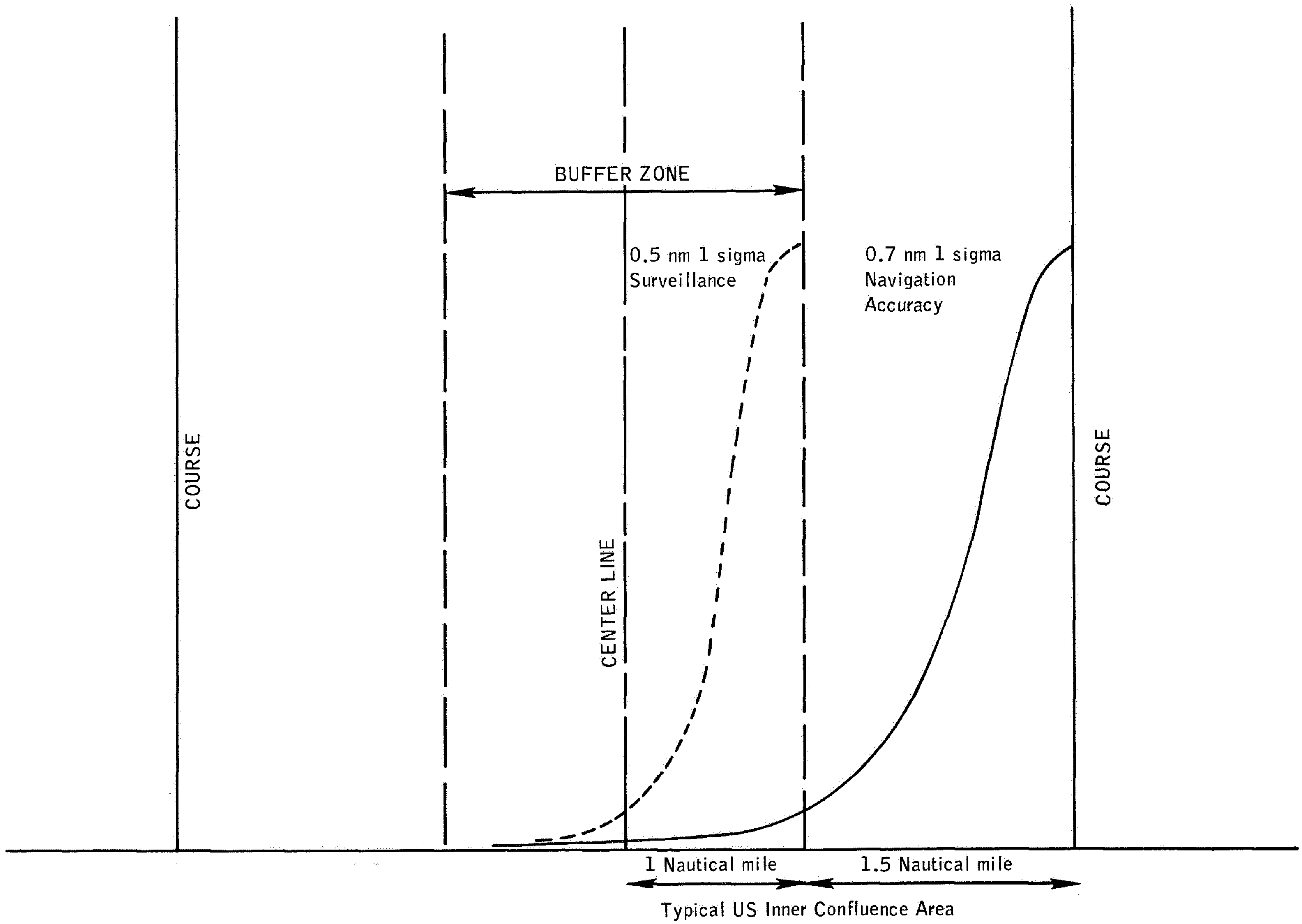


FIGURE 11.7.2 Use of surveillance system in the inner confluence area shipping lanes.

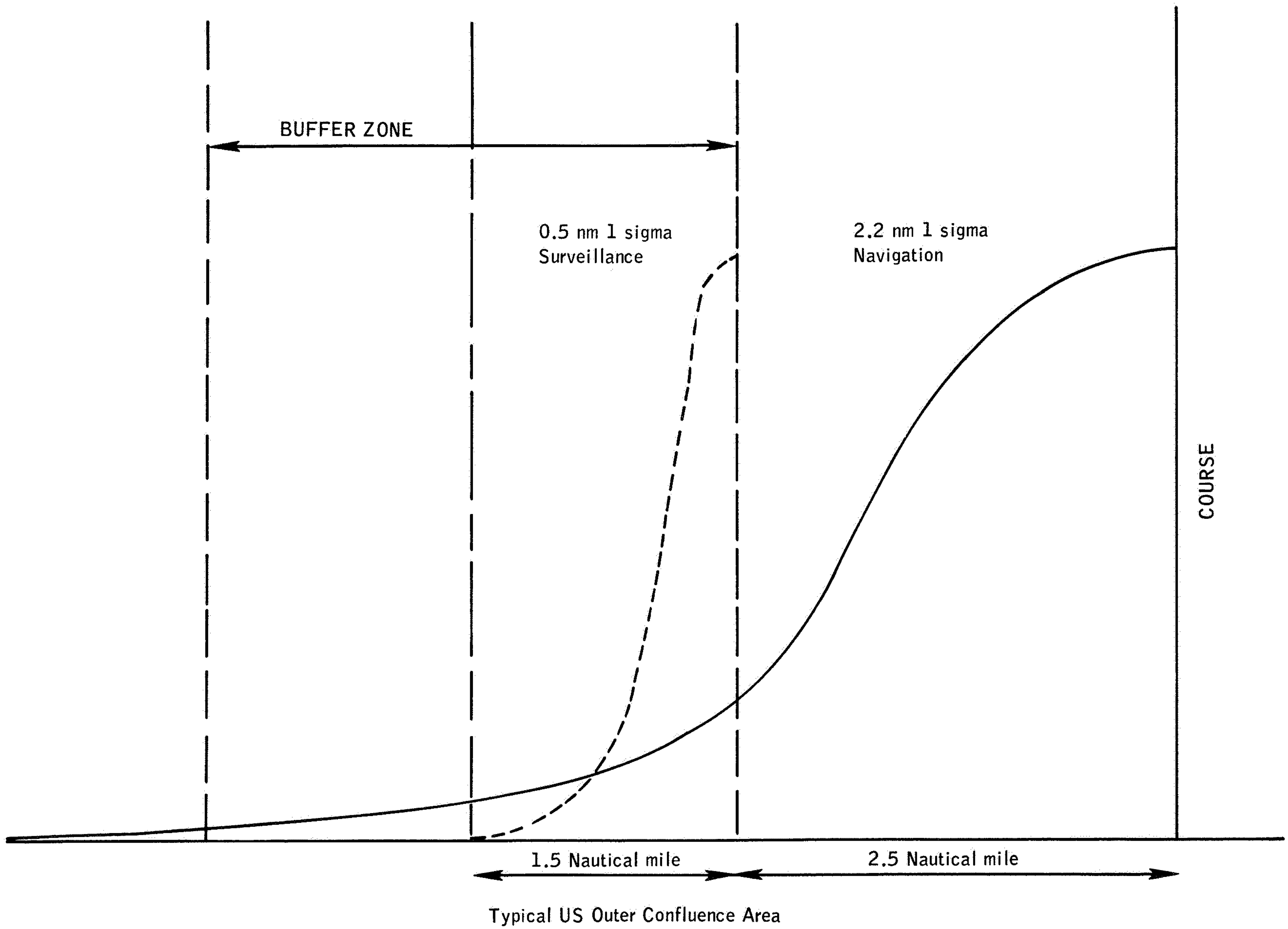


FIGURE 11:7.3 Use of surveillance system in the outer confluence area shipping lanes.

TABLE 11.7.2

TIME REQUIRED TO DEVIATE FROM CENTER TRACK TO EDGE OF BUFFER ZONE (INNER CONFLUENCE AREA- Lane Half-width = 1.5 nm)

Ship Speed (Knots)	Time to go 90 nm (Minutes)	Time to go 18 nm (Minutes)
10	540	108
30	180	36
50	108	22
70	77	15
90	60	12

1° steering must go 90 nm to get off 1.5 nm; 5° steering must go 18 nm to get off 1.5 nm.

Fix interval will be 1/2 time to go off course by 1.5 nm.

TABLE 11.7.3

TIME REQUIRED TO DEVIATE FROM CENTER TRACK TO EDGE OF BUFFER ZONE (OUTER CONFLUENCE AREA- Lane half-width = 2.5 nm)

Ship Speed (Knots)	Time to go 150 nm (Minutes)	Time to go 30 nm (Minutes)
10	900	180
30	300	60
50	180	36
70	130	26
90	100	20

1° steering must to 150 nm to get off 2.5 nm; 5° steering must go 30 nm to get off 2.5 nm.

Fix interval will be 1/2 time to go off course by 2.5 nm.

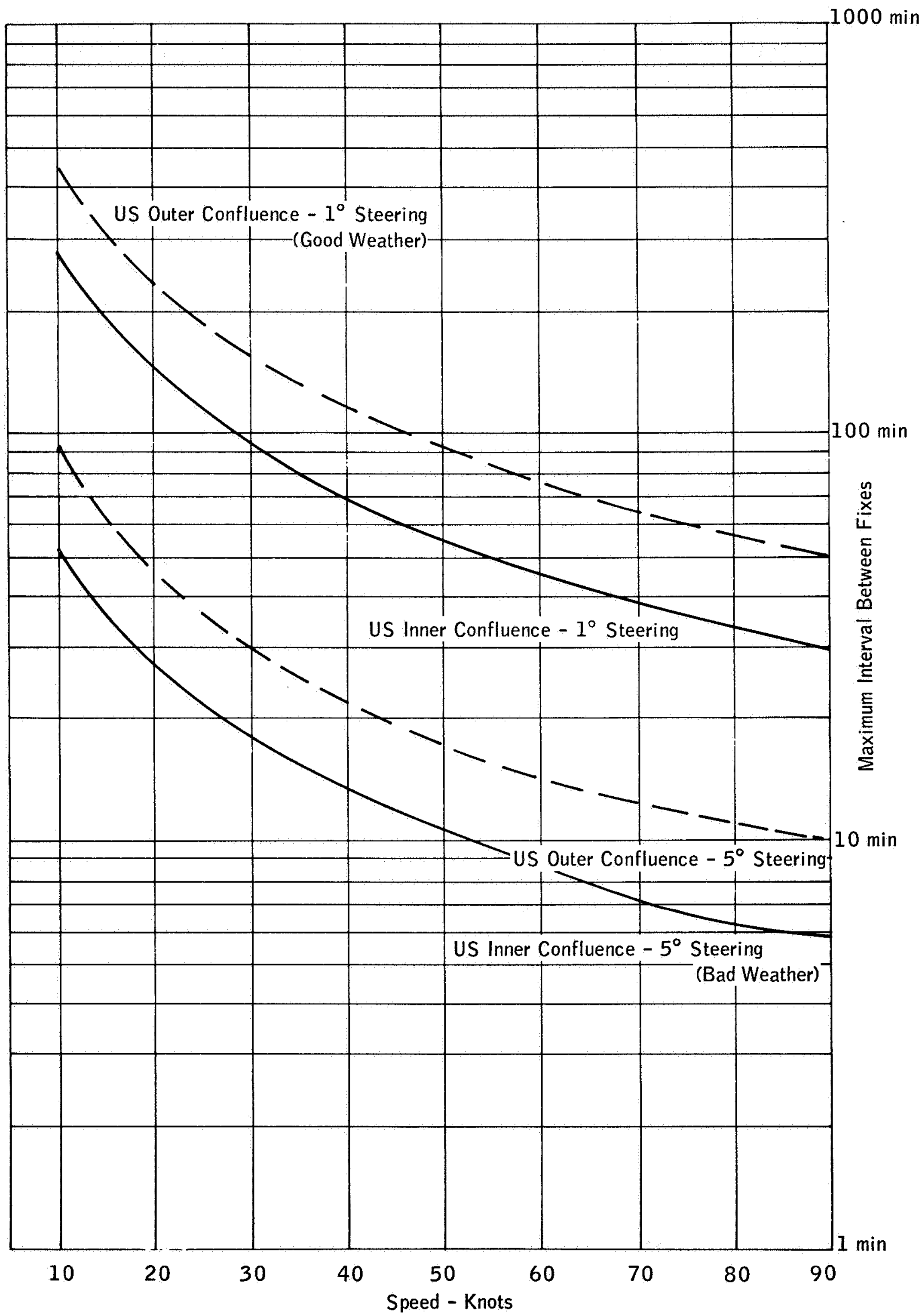


FIGURE 11.7.4 Maximum interval between fixes.

fixes is one-half the time to deviate from the center to the edge of the lane in good weather and bad, and for the outer and inner confluence areas. The dashed portion of the bad weather curves indicates conditions which are considered to be unrealistic, for it seems unlikely that vessels will travel at 50 knots in the confluence areas during the worst weather that they experience.

An examination of Figure 11.7.4 suggests that a single surveillance system using only one radio frequency channel may simultaneously accommodate all of the confluence areas in the Atlantic. It is not likely that all of the confluence areas will be experiencing the worst possible weather at the same time.

It seems reasonable, from an examination of Figure 11.7.4, to select 20 minutes as the average interval between fixes for the average ship. The actual fix rate for an individual ship is selected on the basis of its speed, whether it is in an inner or outer confluence area, and of the weather conditions in the confluence area. The average fix rate of one each 20 minutes can be accomplished through synchronous satellites without time overlap of the interrogations. At a fix rate of 90 per minute, 1800 fixes can be accomplished in such a 20-minute period, which is more than the capacity needed to accommodate the estimated total of 1500 ships in the six confluence areas.

The communication rate between the control agency and the ships depends upon their navigation and steering accuracy. An examination of Figures 11.7.2 and 11.7.3 suggests that there will be a larger number of advisories transmitted to ships in the outer confluence areas (due to their relatively poorer navigation) than in the inner confluence areas. Figure 11.7.3 suggests that ships would be deviated to the edge of the buffer zone approximately 20 percent of the time. Thus, it will be necessary to communicate with at least one out of five ships during the time they are in the outer confluence area. The communication capacity necessary for communicating this rather large number of warnings depends upon whether the communications are digital, teletype, or voice. Voice communication for this purpose is far less efficient than the other methods. One voice channel may be sufficient for the Atlantic if the following conditions are assumed: the total number of ships in the outer confluence areas is 700, the average passage of the ship through the outer confluence area is 5 hours, and one 15-second voice exchange is necessary with each of the ships on the average. One voice channel could accommodate 1200 15-second exchanges in 5 hours, and thus provide adequate capacity for the 700 ships in the outer confluence area. Additional, but smaller, capacity is required for ships in the inner confluence areas. These very rough estimates indicate that a single voice channel through one satellite can accommodate all of the present marine traffic control requirements for the Atlantic Ocean's six confluence areas.

When an inbound ship has completed its passage through the inner confluence area, it arrives in the precautionary area in the vicinity of and including the harbor. The river approach to Rotterdam, Holland, is one of a number of locations equipped with harbor radars and voice communications for marine traffic assistance during periods of low visibility. It is expected that other precautionary areas will be provided with similar facilities which can then be adapted for a traffic control system. The design of marine traffic control systems for use on the high seas and in confluence areas should be integrated with the design of the precautionary area radar traffic control systems. It is not recommended that satellites be used for the precautionary areas where direct line-of-sight radar sensing of ships with high position accuracy is practical, and where direct line-of-sight communications can be used between a precautionary area traffic control center and each of the many ships in the area. It is highly desirable, both economically and operationally, to make the satellite marine traffic-control system compatible with the precautionary area traffic-control system to the extent that the same ship borne equipment and procedures are used for both. It should be possible to switch from one system to the other easily and without confusion. Perhaps this can be accomplished automatically, and the procedures for the ship crew can be made identical for both regions.

A system designed primarily for independent surveillance of positions can also be operated to serve as a navigation aid, by which craft may compute their own positions from measurements of signals received from the satellites. It can also serve as a navigation aid, by determining positions to the craft for automatic display. Navigation is a less urgent requirement than traffic control, since there already exist a rather large number of navigation aids and methods. The value of a satellite system for navigation will depend upon its ability to provide the performance specified in Table 11. 7. 4 over a large region of the earth, and at lower cost than other systems.

Table 11. 7. 4 is part of the report of Special Committee-35, of the Radio Technical Commission for Marine Services (RTCM), "Requirements for a Standard System of Long Distance Electronic Aids to Navigation for International Maritime Use." This table reflects marine navigation requirements as furnished by representatives of U. S. government-industry groups. The report, submitted on December 17, 1957, is presently being updated by SC-60 of the RTCM. This committee, which will study all pertinent electronic aids to navigation, and which was established to help formulate a National Plan for Navigation, has indicated that Table 11. 7. 4 is still generally valid at this date.

7. 2 Position-Fixing Techniques

Determination of a vehicle's current position is fundamental to the navigation and traffic control functions. Figure 11. 7. 5 illustrates some representative position-fixing techniques, which may be conveniently categorized into active and passive systems, depending upon whether or not the vehicle employs a transmit-receive or receive-only mode.

7. 2. 1 Active Techniques

7. 2. 1. 1 Ranging

Ranging measurements from the satellite to the user involve the measurement of propagation time of a radio signal from the satellite to the

TABLE 11.7.4

LONG DISTANCE AIDS TO NAVIGATION

MARITIME REQUIREMENTS AFFECTING THE DESIGN AND CHOICE OF A STANDARD SYSTEM

TYPE OF MARINE USER	COL. 1			COL 2			COL. 3			COL. 4			COL. 5			COL. 6			COL. 7		
	ACCURACY 95% OF TIME			ORDER OF TIME TO OBTAIN POSITION			COVERAGE CAPABILITY OF SYSTEMS			PRESENTATION OF POSITION INFO.			WT. LIMITATIONS (SHIP) (TO INCLUDE ESSENTIAL AUX. EQUIP. SUCH AS COMPUTERS, RECORDER, TRACK PLOTTER, POS. INDICATOR, ETC.)			SIZE LIMITATIONS (SHIP) (TO INCLUDE ESSENTIAL AUX. EQUIP.)			COST LIMITATIONS (PER COMPLETE EQUIP. INCLUDING AUX. EQUIP. BUT EXCLUSIVE OF INSTALLATION COSTS.)		
	1. 0 - 0.1 MILE 2. 0.1 - 0.5 " 3. 0.5 - 1.0 " 4. 1.0 - 2.0 MILES 5. 2.0 - 4.0 " 6. OVER 4.0			1. INSTANTANEOUS 2. 15 SEC. - 1 MIN. 3. 1 MIN. - 3 MINS. 4. 3 MINS. - 10 " 5. OVER 10 MINS.			1. WORLD WIDE 2. WORLD WIDE LESS POLAR REGIONS 3. NORTH ATLANTIC & NORTH PACIFIC			1. PROGRAMMED NAV. WITH CONTROL 2. AUTOMATIC TRACKING 3. DIRECT READING LAT. & LONG. 4. DIRECT READING OF SYS. COORDINATES. 5. MANUALLY OBTAINED DATA FROM WHICH POS. MAY BE PLOTTED. 6. ACOUSTIC OR VIDEO DATA FROM WHICH POS. MAY BE PLOTTED.			1. NOT TO EXCEED 50 LBS. 2. 50 - 150 LBS. 3. 150 - 500 " 4. OVER 500 LBS.			1. NOT TO EXCEED 2 CU. FT. 2. 2 - 5 CU. FT. 3. 5 - 20 " " 4. OVER 20 CU. FT.			1. UNDER $500. 2. $ 500 - $1500. 3. 1500 - 5000 4. 5000 - 20,000. 5. OVER $20,000.		
	PRESENT	1962–1975	ULTIMATE	PRESENT	1962–1975	ULTIMATE	PRESENT	1962–1975	ULTIMATE	PRESENT	1962–1975	ULTIMATE	PRESENT	1962–1975	ULTIMATE	PRESENT	1962–1975	ULTIMATE	PRESENT	1962–1975	ULTIMATE
LARGE PASSENGER	4	2	1	3	1	1	3	2	2	4	2	1	4	4	4	4	4	4	4	4	5
MEDIUM PASSENGER	4	2	1	4	2	1	3	2	2	4	2	1	4	4	4	4	4	4	4	4	5
SMALL PASSENGER	4	2	1	4	2	2	3	2	2	4	3	3	3	3	3	3	3	3	4	4	4
LARGE CARGO	4	2	1	3	1	1	3	2	2	4	2	1	4	4	4	4	4	4	4	4	5
MEDIUM CARGO	4	2	1	4	2	2	3	2	1	5	4	3	4	4	4	4	4	4	3	3	4
SMALL CARGO	4	2	1	4	2	2	3	2	1	5	4	3	3	3	3	3	3	3	2	3	4
LARGE TANKER	4	2	1	3	1	1	3	2	2	4	2	1	4	4	4	4	4	4	4	4	5
MEDIUM TANKER	4	2	1	4	2	2	3	2	1	4	3	3	4	4	4	4	4	4	4	4	4
SMALL TANKER	4	2	1	4	2	2	3	2	1	5	4	3	3	3	3	3	3	3	2	3	4
LARGE FISHING CRAFT	3	2	1	4	2	1	3	2	1	5	4	2	2	3	3	2	3	3	3	3	4
SMALL FISHING CRAFT	3	2	1	4	3	2	3	2	1	6	4	4	2	2	2	2	2	2	2	3	3
CABLE LAYERS	2	2	1	1	1	1	3	2	2	2	2	2	4	4	4	4	4	4	4	4	4
LARGE PRIVATE CRAFT	5	4	2	4	2	1	3	2	1	5	4	2	2	3	3	2	3	3	3	3	4
SMALL PRIVATE CRAFT	5	4	2	4	3	2	3	2	1	6	4	4	1	1	1	1	1	1	1	2	2
LARGE COMBATANT	2	2	1	1	1	1	2	1	1	2	2	1	4	4	4	4	4	4	5	5	5
MEDIUM COMBATANT	2	2	1	1	1	1	2	1	1	2	2	1	4	4	4	4	4	4	5	5	5
SMALL COMBATANT	2	2	1	1	1	1	2	1	1	2	2	1	3	3	3	3	3	3	5	5	5
LARGE AUXILIARIES	4	2	1	2	1	1	1	1	1	4	2	1	4	4	4	4	4	4	4	5	5
MEDIUM AUXILIARIES	4	2	1	2	1	1	1	1	1	4	2	1	4	4	4	4	4	4	4	5	5
SMALL AUXILIARIES	4	2	1	2	1	1	1	1	1	4	2	1	3	3	3	3	3	3	4	5	5
OCEANOGRAPHIC	3	2	2	4	3	2	2	1	1	4	4	4	4	4	4	4	4	4	3	3	3
HYDROGRAPHIC	1	1	1	1	1	1	1	1	1	2	2	2	4	4	4	4	4	4	5	5	5
MAGNETIC SURVEY	1	1	1	1	1	1	1	1	1	2	2	2	4	4	4	4	4	4	5	5	5
LARGE COAST GUARD	3	2	1	2	1	1	2	1	1	4	2	1	4	4	4	4	4	4	4	5	5
SMALL COAST GUARD	4	3	1	3	2	1	2	1	1	4	4	2	3	3	3	3	3	3	4	4	5
SUBMARINES	2	2	1	2	1	1	1	1	1	2	2	1	2	2	2	2	2	2	5	5	5
ICE BREAKERS	3	2	1	2	1	1	1	1	1	4	2	1	4	4	4	4	4	4	4	5	5

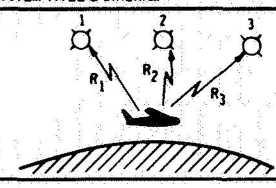
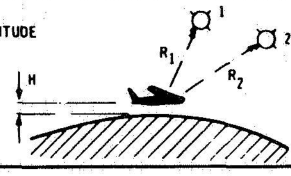
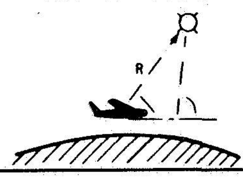
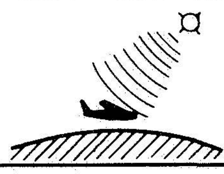
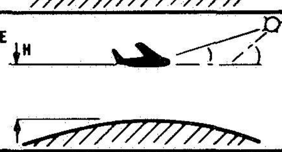
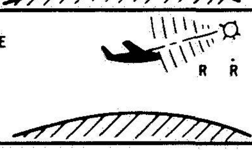
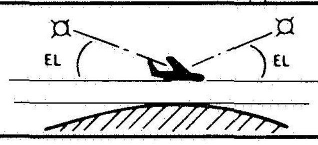
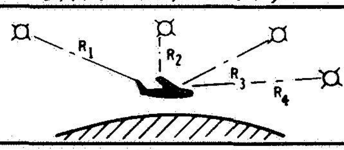
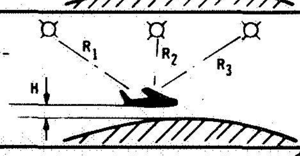
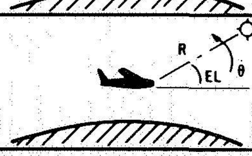
SYSTEM TITLE & DIAGRAM		SAT'S REQ'D	MEASUREMENTS PERFORMED	SURFACES OF POSITION
A RANGING		3	RANGE CRAFT SAT 1 RANGE CRAFT SAT 2 RANGE CRAFT SAT 3	3 SPHERES
B RANGING - ALTITUDE		2	RANGE CRAFT SAT 1 RANGE CRAFT SAT 2 ALTITUDE	3 SPHERES
C ANGLE - RANGE		1	RANGE CRAFT SAT 2 ANGLES CRAFT SAT	1 SPHERE 2 CONES
D DOPPLER		1	FREQUENCY	1 HYPERBOLOID (PER PAIR OF MEASUREMENTS)
E ANGLE - ALTITUDE		1	ALTITUDE 2 ANGLES	1 SPHERE 2 CONES
F RANGE - RANGE RATE		1	RANGE RANGE RATE *RADIAL ACCELERATION*	2 SPHERES *1 HYPERBOLOID*
G ELEVATION - ALTITUDE		2	ALTITUDE 2 ELEVATION ANGLES	1 SPHERE 2 CONES
H RANGE DIFFERENCE		4	$\Delta R = R_1 - R_3$ $\Delta R = R_1 - R_2$ $\Delta R = R_2 - R_3$	3 HYPERBOLOIDS
I RANGE DIFFERENCE - ALTITUDE		3	$\Delta R = R_1 - R_2$ $\Delta R = R_1 - R_3$ ALTITUDE	2 HYPERBOLOIDS *1 SPHERE*
J RANGE - ELEVATION ANGLE		1	RANGE ELEVATION ANGLE ELEVATION ANGLE RATE	1 SPHERE 2 CONES

FIGURE 11.7.5 Representative navigation satellite system approaches.

user and return. Assuming that the propagation velocity is known, the propagation time measurement is readily converted to range.

Propagation time measurement involves the transmission of a time marker on a radio signal from a ground station to a satellite that retransmits it to a user. It is returned by the user to the satellite, which retransmits it again. The ground station measures the time between the two transmissions of the marker by the satellite and thus determines twice the propagation time from the known position of the satellite to the user. This is sufficient information to determine a circle of position for a ship. For an aircraft, the altitude must also be known, if an accurate fix is desired. Altitude may be automatically transmitted from the aircraft via the satellite. There are many ways to introduce time markers on the radio signal. The choice among them must be made on the basis of the amount of energy that can be transmitted from the satellite, time available for measurement, user equipment complexity, cost, and compatibility with voice and digital communications. Range-measurement accuracy is not a function of range, and does not require knowledge of reference directions at the satellite. Range measurement is fairly easy to implement, requiring simple transponders on the satellite and user craft. In all respects, the technique is within the state of the art.

7.2.1.2 Angle Measurement

Angle measurement by a spaceborne system is an approach which has certain desirable aspects. A typical system of this type includes a pair of crossed-baseline spaceborne interferometers extended from a single satellite. Each interferometer baseline has a dimension equivalent to a large number (e.g., several hundred) of wavelengths. The length of the baseline determines the number and angular dimension of the grating lobe structure subtended by the aperture. It is the resolution provided by the grating lobe structure of the interferometer that makes possible the accurate angular measurement of a position in space by the system. The angle measurement technique provides a significant advantage, in that full coverage for a specified tactical region of interest may be provided by a single, synchronous-orbit satellite. Additionally, the measurement from a single satellite provides altitude, thereby providing a position fix which is independent of other on-board sensors, and a true position fix can be obtained at the equator with geostationary orbits - in contrast to the line of position obtained with a ranging system.

7.2.1.3 Relay of Ground-Based Aids

A promising approach to position fixing for both air and marine application is the cooperative use of ground-based radio navigation aids. Signals from the ground-based aids are received by the user craft and automatically transmitted through a satellite to a ground station where the fix is determined, used for air traffic control or other purposes, and, if desired, also transmitted back through the satellite for display aboard the craft.

Any ground-based aid with the coverage and accuracy requirements of the user may be used. A very promising aid is Omega, and its use is under investigation by NASA in its Omega Position Locating Equipment (OPLE) system.

OPLE uses a satellite only as a communication relay. Position-fix data are received aboard the user craft from the ground-based Omega system and then transmitted through a satellite to a ground station. The data consist of phase difference measurements from two or more pairs of Omega VLF stations. OPLE takes advantage of the existence of Omega, which has proven to be highly effective. It is expected to be available on a world-wide basis before 1975. There will be no gaps in coverage at the equator or poles, as with a direct-range measurement system using geostationary satellites.

OPLE requires only one satellite in view, and its location and altitude do not affect the accuracy of position fixes, since it does not serve as a position or direction reference. It serves only as a communication relay. OPLE does require that the user carry a VLF antenna and receiver in addition to the equipment for communicating with the satellite. Like OMEGA, OPLE requires the resolution of lane ambiguities which occur every time the difference in phase between a station pair changes by one cycle.

7.2.2 Passive Techniques

Passive techniques require no transmission from the user; thus, system saturation by many simultaneous users does not occur. It is necessary for the user to compute his own fix. This requires him to receive signals from the satellite, from which he can determine his position relative to the satellite location if he knows the location of the satellite at the time he receives the signals.

Information concerning the location of the satellite must be distributed to users frequently enough so that they can compute the location to the desired accuracy. For low and medium orbit satellites, this usually requires broadcasting updated ephemeris data from the satellite. The ephemeris data are transmitted from a ground station and recorded in the satellite at intervals as short as 12 hours, for frequent rebroadcast by the satellite as it orbits the earth. Geostationary satellites may be station kept, or else their ephemeris data may be distributed as a weekly or monthly publication. Some passive techniques perform best with timing signals relayed by the satellite in real time. Ephemeris data may then be relayed through the satellite without the need for recording in the satellite.

7.2.2.1 Doppler Measurements

Doppler measurement from a system of low altitude satellites is an approach of proven capability which is successfully used in the TRANSIT (Navy Navigation Satellite) program.

In operation, the range rate of the satellite relative to the user is determined by measuring the doppler shift of a continuous wave signal transmitted by the satellite. There is a unique "doppler curve" for every location within range of the satellite during its pass above the horizon. Ambiguity on the two sides of the path is resolved by rotation of the earth during the pass.

Since each doppler curve is unique, the user's position can be determined from the curve, if the satellite orbit is known accurately. The technique works best with low orbit satellites that have a high velocity relative to the users.

In the TRANSIT system, each satellite radiates continuously at 150 MHz and 400 MHz. Using the known frequency-dependence of ionospheric influence on the doppler shift, the use of these two frequencies permits an accurate correction for ionospheric errors (equivalent to a single frequency measurement at 3 to 4 GHz).

In the simplest mode of use, the doppler shift is integrated to generate range differences by the straightforward but very accurate procedure of counting doppler cycles between the times of reception of two-minute time markers broadcast by the satellite. This method is fundamentally a range difference or hyperbolic navigation scheme in which the successive positions of the satellite at 2-minute intervals serve as reference points.

In the present TRANSIT configuration, this approach requires the use of a relatively complex processing procedure, accurate knowledge of craft velocity, as well as a large number of satellites, for near continuous navigation coverage. However, a considerable simplification could be effected in both user equipment and computations by the use of "constant ground-track" orbits, that is, orbits with periods of 1/13 or 1/14 of a day, for example, which repeat their ground track each day. In this way, a 24-hour ephemeris could describe the orbit of a satellite for its entire operating life, and a table look-up scheme which has been devised could satisfy the computation requirement. It appears feasible to achieve orbital control to the needed accuracy.

The influence of ship's velocity on position accuracy can be removed by explicit solution of this parameter simultaneously with position, from the satellite measurements. This method has been successfully demonstrated in shipboard experiments, but is not yet being used operationally.

Difficulties which are fundamental to and cannot be avoided in the doppler method are the time required for satellite observation (which makes the method cumbersome for high-performance aircraft), the fact that it cannot be applied to a geostationary satellite (which is an obvious choice for traffic control), and the inability of the method to provide good altitude measurements.

7.2.2.2 Direct Range Measurements

Range measurement from multiple satellites provides a means for instantaneous position location by determination of the intersection of the multiple spheres of position. Minimally, two satellites and aircraft altitude information are required. For an instantaneous position determination completely independent of aircraft-derived inputs, three satellites are required. Two satellites allow an instantaneous determination of the aircraft altitude is known, or may provide a non-instantaneous determination of a moderate time-base of data is employed. The principal advantage of ranging systems relates to their simplicity and the attendant ease in obtaining a position determination. A disadvantage is the multiplicity of satellites required for its implementation.

In passive direct-range measurement, pulses or other timing markers are transmitted from the satellite at a known real time, say on the real-time second. Real-time accuracy at the satellite should be on the order of a microsecond or less, and the user must have a stable clock on his vehicle. When the user is at a known location, such as a surveyed location at an airport or harbor, he sets his clock so that it generates a reference pulse that precedes the reception of the pulse received from the satellite by the known propagation time from the satellite to his known position. By this means he sets his clock in real-time synchronization, from the time of transmission of the onboard clock pulse to the reception of the signal from the satellite, to give a direct measure of range from the known position of the satellite to the vehicle. If this is accomplished from two satellites, the user has determined three spheres of position: two centered on the satellites with the measured ranges, and the third centered at the earth's center, with the earth's radius known.

For an aircraft in flight, the independently determined altitude must be added to the earth radius. Thus, measuring the range from two reasonably-spaced satellites will provide two lines of position on the earth's surface, ambiguous only as to hemisphere. This direct-ranging technique would require only two satellites for North Atlantic coverage, with one ground station to serve the pair. Six satellites, equally spaced at synchronous altitude, would provide navigational fixes over the primary areas of interest, with coverage gaps at the poles. Since the circular lines of position are centered about equatorial sub-satellite points for uninclined synchronous orbits, the crossing angles of the circles decrease with user latitude, resulting in an equatorial band several degrees wide, within which an accurate fix cannot be provided although lines of position are determined.

It is necessary that the stability of the oscillator driving the user's clock be compatible with the accuracy of the fixes desired during the flight or voyage. For the duration of a transatlantic flight, an oscillator having an accuracy of one part in 10^{10} per day will accumulate a range error of about one-half mile, which is adequate for entering a regional over-land control area. Time references with such stability may cost $10,000-20,000. For limited applications, less expensive oscillator clocks might be recalibrated by comparison with a position fix determined by a different technique, for example, the range-difference method.

7.2.2.3 Range-Difference Measurements

Range-difference measurement between pairs of satellites provides a conventional hyperbolic position determination from spaceborne stations. Hyperbolic techniques have been used successfully for a number of years, particularly for long and medium range over-ocean navigation, in such systems as loran, Decca, and Omega. A principal disadvantage of the technique for satellite application is the large number of satellites required for extensive earth coverage.

This type of system does not require the user vehicle to have a stable time standard, but rather that it be able to accurately measure time differences as opposed to absolute time. It is necessary that the pulses be transmitted from two satellites at different locations, either at exactly the same time, or with a fixed known delay between their transmissions. The time differences between the reception of pulses from the two satellites define hyperbolic surfaces of position, intersecting the earth's surface to give the user's location in a manner similar to that of loran. Alternatively, range sums may be used to give elliptical lines of position. These do not give any different information than the hyperbolic lines; thus the same two satellites cannot be used for two lines of position. The measurement from each pair of satellites yields a hyperbolic line of position, and the crossing of the hyperbolic lines of position taken from more than one pair of satellites yields the user's location.

Since time differences from two pairs of satellites are required, at least three satellites must be visible simultaneously. Therefore, the longitudinal spacing of synchronous satellites must be closer than for the direct-range measurement technique. Adequate coverage for the range-difference method can be provided by geostationary satellites with a longitudinal spacing of 30°. This would require 12 satellites for full earth coverage. As in the direct-ranging system, the hyperbolic lines of position all cross the equator at right angles, and yield no fixes at that point. If the pulses are transmitted simultaneously from the two satellites of a pair, the hyperbolic method will also have a narrow unusable region along the perpendicular bisector of the baseline, in the region in which the pulses from the two satellites overlap, and it is not possible to resolve them to determine their time difference; therefore, an offset time should be allowed. Improved coverage for the hyperbolic system may be achieved by using additional satellites in inclined orbits. Further analysis is required to determine the optimum configuration.

Equipment for the hyperbolic mode of operation will be less expensive than for the ranging method, because of the absence of a long-term stable clock. Fix determination from the direct-range measurements may be somewhat simpler than for the range-difference or hyperbolic mode.

7.2.2.4 Angle Measurements

Various passive angle measurement techniques have been developed, differing in means for generating the angles in space (at the satellite or the user) and in the method of measurement by the user. The three major systems are: (1) angle generation by means of crossed interferometers, with phase measurement by the user; (2) angle generation by means of crossed rotating fan beams, with an omnidirectional time reference and epoch measurement by the user; and (3) radio sextant measurement by the user.

One implementation of the angle-measurement approach is to utilize spaceborne, crossed-baseline interferometers. This approach consists of a system of four antennas at the end of booms extending from the satellite to form two orthogonally oriented baselines, each of which is in a plane approximately parallel to the earth's surface in the region of the subsatellite point. The two crossed-baseline pairs of antennas may be used to establish two independent angle measurements relative to the baseline orientations for the aircraft position near the surface of the earth.

The user craft receives transmissions from the satellite interferometer system, and the received difference in phase is determined for the signals associated with the appropriate baseline configuration. The phase-difference measurement is directly related to the angle formed by the line of direction from the aircraft to the center of the baseline and the baseline orientation. This angle defines a conical surface of position on which the aircraft is located. A second conical surface of position is defined by the angle reference to the second baseline. The intersection of the two conical surfaces with the sphere defined by the altitude of the aircraft provides a solution for the position of the aircraft. Alternatively, the signals from the interferometer antennas may be swept in phase to provide a lobe pattern that scans in angle. The user determines the epoch of the nulls in the lobe pattern as it scans past his location, and derives his direction relative to the baseline of the satellite interferometer.

The feasibility of angle-measurement methods depends on the accuracy of the satellite altitude determination. The following example provides some appreciation of the accuracy with which satellite altitude must be known.

For the situation where the range between the user aircraft and the satellite is nominally 20, 000 miles (corresponding to the synchronous altitude case), an uncertainty of one milliradian of arc in the determination of spacecraft altitude will result in an uncertainty of about 20 to 50 nautical miles in the position of the aircraft. An angular resolution of about 5 microradians or better is required for accuracies in the range of 0. 1 nautical mile.

A variation of the single satellite angle-measurement approach employs the addition of a range measurement. This technique is usually considered for use with an active system, but appears to have potential for operating in the passive mode.

In this approach, a satellite-borne angle-measurement device, such as long-baseline interferometers operating at a selected radio frequency, determine the pointing angles from satellite to user vehicle, and additionally establish the range from satellite to aircraft. The implementation requires the same baseline altitude information, since the orientation of the interferometer axes must be accurately known for the angle determination involved.

7.3 System Models for Cost Analysis

The foregoing discussions illustrate the considerable breadth of possible navigation/traffic control systems which may be employed. Choices will be made among the set of system options which include: (a) basic measurement technique, (b) number of satellites required for implementation, (c) orbit configuration, (d) passive or active operation, (e) two- or three-dimensional position determinations (including altitude) (f) instantaneous or time sequenced measurements, (g) satellites self-contained or ground station controlled, and (h) type of system employed for tracking of the satellites.

Among this very large number of combinations, a reasonable set of alternatives are feasible, contingent upon the user population and their preferences, anticipated growth factors, and the influence of international agreements.

To accomplish the cost analyses made in Section 8, a set of six possible systems were defined, representing various stages in the evolutionary growth of an international system, or different degrees of service, consistent with various user demand levels. The systems are summarized in Table 11.7.5, and the corresponding costs and benefits for each level of service are presented in Section 8.

System 1

One geostationary satellite serving transoceanic traffic with aeronautical communication service in the VHF band. The system will have a limited number of air and marine communications channels, one of which may be used for ranging, to provide cross track monitoring on principal routes.

System 2

Two geostationary satellites serving transoceanic traffic with aeronautical communication service in the VHF band. The system will provide range or range-difference position fixing, and an air traffic control capability sufficient for reduced spacing of aircraft. Limited capability for marine service will be included.

System 3

Two geostationary satellites serving transoceanic traffic in both the VHF and L bands. The satellites will provide range or range-difference position fixing, voice and data communications for MTC and ATC surveillance.

System 4

Two operational geostationary satellites serving transoceanic traffic with voice and data communications at L band and position fixing by ranging. (A passive system would require three satellites.) Both aeronautical and marine services will be provided.

System 5

One geostationary satellite serving transoceanic traffic with communication capability at L band and position fixing by angle measurement at L or C band.

System 6

A completely operational worldwide system, based upon System 4 or 5, employing six geostationary satellites (twelve, if a passive ranging is employed, or a minimum of three if angle measurements are used).

TABLE 11.7.5

SIX POSSIBLE SATELLITE SYSTEMS

System	Description	Frequency band	Number of Satellites	Satellite		Number of Ground Stations	Complexity of User Equipment		Earliest Date of Service
				weight lbs.	ERP kw		Air	Marine	
1	Transoceanic voice communication and ranging	VHF	1	200-300	0.5-1	1	A	D	1970
2	Transoceanic data and voice communication position fixing by ranging; ATC	VHF	2	200-300	0.5-1	2	A	D	1971
3	Transoceanic data and voice communication position fixing by ranging; ATC	VHF and L	2	800-1000	5-10	2	B	B	1973
4	Transoceanic data and voice communication position fixing by ranging operational ATC	L	2	800-1000	5-10	2	B	B	1975
5	Transoceanic voice communication position fixing by angle measurement	L or C	1	800-1000	5-10	3	C	B/C	1978
6	Worldwide operational marine and air navigation and traffic control	L or C	6	800-1000	5-10	6	C	B/C	1980

Key for User Equipment

A - less complex, includes minimal communications and ranging capability
B - more capability, antenna system may be complex if high gain, steerable units are required
C - greatest complexity, particularly if on board computer is used
D - determined by extent of marine participation in these systems

8.0 ECONOMIC CONSIDERATIONS

This section presents a cost-benefit analysis for the development, launch, and operation of a satellite system for navigation and traffic control of aircraft and ships. A satellite system consists of satellites, a ground complex, and equipments installed in the aircraft and ships that use the system. The system may have worldwide application, or be limited to one or more areas. Costs and benefits have been worked out for systems that provide services for a high density transoceanic area (in this case the Atlantic), and for one that provides services on a worldwide scale. Those benefiting from the satellite navigation and traffic control systems have been divided into groupings of U.S.-owned aircraft and ships and U.S. plus foreign-owned aircraft and ships. The numbers of beneficiaries grow with the passage of time after the introduction of the system.

The alternative means for accomplishing the objective have been identified as the six representative candidate systems described in Section 7.3, and costs and benefits have been estimated for them. R&D costs relate to the design and development of the flight models of the satellites, but not to the costs of other R&D before that point. Original launch costs cover the satellite portion of the system; and ground complex costs are associated with the earth portion of the system. These three are equivalent to capital costs. The operational costs include salaries of personnel, and maintenance of the ground complex, plus replacement of satellites.

An air traffic-control agency is already in operation and is paid for from other sources. The satellite system will provide inputs to it and receive outputs from it, but will not materially expand its size or affect its cost. A marine traffic-control agency does not yet exist. Since a satellite system appears to be essential for it to function, it may come into being as a part of the satellite system. Its costs, therefore, are added to the costs of the ground complex.

There are likely to be no indirect costs associated with a satellite system, since the various regulatory and advisory bodies that already exist appear capable of absorbing the responsibilities of the new system without appreciable expansion.

8.1 Costs

8.1.1 Assumptions

The Delta launch vehicle will place approximately 290 lbs in geostationary orbit at a cost of \$5M. Heavier satellites will require launch vehicles costing about \$15M.

The R&D cost (as defined in Section 8.0) of a satellite appropriate for navigation and traffic control is $10 - $20M for a small satellite and $20 - $50M for a large satellite.

The lifetime of the satellite will average 5 years.

A factor of 1.2 will account for launch malfunctions.

Aircraft users will have dual equipments. Ship users will have single equipments.

It has been suggested that the eventual navigation and traffic control satellite system may develop on an incremental basis, by the growth of a rudimentary system into one capable of satisfying an increasing spread of needs. In surveying the economic considerations, however, total costs and total benefits have been calculated for each system as an entity. Incremental costs and incremental benefits could be computed, if that were desirable.

8.2 Benefits

8.2.1 Cost Reductions and Benefits to Ultimate User

The four most readily quantifiable cost-reduction categories are considered in detail. There will most likely be a cost reduction in air/sea rescue services because the number of incidents will be fewer, and also because the survivors are likely to be found more quickly. The dollar savings, of this type, are small as compared to the others, however, and, therefore, air/sea rescue services were not considered in detail.

Another cost reduction is identified but not assigned a dollar value. It concerns the reduction of losses that occur in a business due to disruption of materials flow. For example, if an oil tanker is damaged in collision or grounding, the direct cost of repair is reflected in increased insurance rates in subsequent years. But the absence of that tanker from her regularly scheduled run may result in an oversupply of crude at the well-site, as well as lack of crude at the refinery. Storage tanks may not be adequate to enable the wells to continue pumping nor the refinery to continue processing. The result may be the shutting down of one or both operations, a measure far more costly than the repairs to the ship. Conversely, the increased safety provided by the navigation and traffic control satellite system should prevent many such expensive disruptions.

Two important benefits to the ultimate users of transportation systems, not quantitifiable, are:

Increased safety of life

Convenience of on-time arrival

TABLE 11.8.1

COSTS ASSOCIATED WITH SYSTEMS DESCRIBED IN SECTION 7.3

SYSTEM (1-5 are Atlantic Area, 6 is worldwide)	(Million Dollars)					
	1	2	3	4	5	6
Capital Equipment Costs						
R&D	10-20	10-20	20-40	20-40	30-50	20-40
No. of Satellites	1	2	2	2	1	6
Cost of Flight Model Satellites	2-4	2-4	6-9	6-9	7-10	6-9
Cost of Launch (per satellite)	5	5	15	15	15	15
Total Cost of Satellite Portion of System (R&D plus satellites plus launch, including 1.2 malfunction factor)	18-31	27-42	70-98	70-98	56-80	171-213
Ground Complex Costs (including Marine Control for systems 3-6)	3-4	3-4	6-8	6-8	6-8	18-24
Total Capital Costs	21-35	30-46	76-106	76-106	62-88	189-237
Operation and Maintenance of Ground Complex (per year)	2-3	2-3	3-5	3-5	3-5	9-15
Replacement of Satellites (per year)	1.6-2	3.2-4	5-11.5	5-11.5	5.3-6	15-35
Total Annual Costs	3.6-5	5.2-7	8-16.5	8-16.5	8.3-11	24-50
User Equipment Costs	(Thousand Dollars)					
Capital Costs (equipment + installation)						
Aircraft users (each)	20-40	20-40	20-40	60-120	60-120	60-120
Ship users (each)	*	7-15	25-50	25-50	25-50	25-50
Operation and Maintenance (per year)						
Aircraft users (each)	2-4	2-4	2-4	6-12	6-12	6-12
Ship users (each)	*	.7-1.5	2.5-5	2.5-5	2.5-5	2.5-5

*not appropriate

Another benefit, not quantitifiable, relates to improved communications between aircraft and ground terminals for management and operational control.

A review has been made of published literature (e.g., Attwooll, Dunmire) and of private studies of benefits of various satellite systems for navigation and traffic control. Consultation and advice has been received from government officials, executives of air and ship operating companies, and insurance underwriters. Table 11.8.3 represents the Panel's interpretation of all the information received.

It is recognized that some studies have quantified benefits which this Panel considered to be non-quantifiable. It is further recognized that the estimated benefits of some studies have been higher than those of this Panel; (e.g., an estimated average diversion penalty of up to $1000 per flight for the SST by 1980, compared to $160 per flight estimated in this report). It is also recognized that there is need for a more extensive study and analysis of the costs and benefits of satellite systems for navigation and traffic control, - more extensive than was possible in this Summer Study. Nevertheless, the Panel has made and presents its own cost-benefit analysis, conservative though it may be by other standards.

8.3 Cost vs. Benefits

Curves have been drawn for the range of cumulative costs and the range of cumulative net benefits for a ten-year period following the availability of the satellite segment of the system. For each system, the net benefits to U.S. users and the net benefits to U.S. plus foreign users are depicted (except System 1, which provides so little in benefits for navigation and traffic control services that it has no cost-benefit advantages). A system may be said to have unquestionable cost-benefit advantages at the point where the lowest estimate of benefits exceeds the highest estimate of costs.

Within the time frame, Systems 3, 4, 5 and 6 reach that point only if U.S. plus foreign users are added together. They do not reach that point for U.S. users alone.

System 2 does not reach that point within the arbitary 10-year time frame but might reach it if the benefits (which are a reflection of increasing congestion in the air space) continue to grow at a greater than linear rate. System 2 might be placed in orbit as an aeronautical services satellite. If less than the full cost of the System were assigned to navigation and traffic control services System 2 might reach the cost-benefit advantages point earlier.

The cost-benefit advantages to the maritime industry greatly exceed those to the aviation industry.

TABLE 11.8.2

QUANTIFIED BENEFITS (cost reductions) OF SIX SYSTEMS

SYSTEM	1	2	3	4	5	6
BENEFIT						
1. Improvement in Air Traffic Control	very limited	x	x	x	x	x
2. Marine Traffic Control		x	x	x	x	x
3. Enroute Navigation for Ships			x	x	x	x
4. Aid to Commerical Fishing			x	x	x	x

x = applicable

TABLE 11.8.3

BENEFITS OF VARIOUS SATELLITE SYSTEMS (Panel interpretation of all information received)

Benefit	Beneficiary	Reason for Benefit	Average Monetary Return per Year per Aircraft or Ship	Average Net Monetary Return per Year per Aircraft or Ship - 10 yr. amortization of costs of user equipment*
Improvement in Air Traffic Control	Owners of Aircraft	Savings in fuel and increased utilization of aircraft by reduction in enroute delays	Reduction in delay for 700 flights per year at $20-40 savings per flight in an early time frame, rising to $80-160 per flight by 1980, $14K-28K to $56-102K	$2-4K rising to $44-88K
Marine Traffic Control	Owners of Ships	Reduction in insurance premiums through increased safety	Lowering of negotiated rate of premium if experience warrants it by 0.5%-1.0% of cost of vessel, ($10M-20M average cost) $50K-200K	(A ship would receive benefits from both with a single installation of equipment) $51K - $202K
Enroute Navigation for Ships	Owners of Ships	Savings in fuel and increased utilization of ships by improved course keeping	1% of fuel cost (300K - 500K); 1% gain in days available for revenue carrying purposes ($300K-$700K per year), $6K - $12K	
Aid to Commercial Fishing	Owners of Ships	Savings in manpower and fuel by enabling ship to return directly to proven fishing grounds	10% of manpower and fuel costs, ($50K-$250K per year) $5K - $25K	Zero - $15K

*Column 4 less user costs from Table 11.8.1

K = Thousand
M = Million

TABLE 11.8.4

NUMBER OF USERS BENEFITING AND TYPE OF BENEFIT AT END OF FIRST YEAR AND DURING TENTH YEAR AFTER SATELLITE SEGMENT OF SYSTEM BECOMES AVAILABLE

BENEFIT	FIRST YEAR		TENTH YEAR	
	Atlantic Area	Worldwide System	Atlantic Area	Worldwide System
Improvement in Air Traffic Control	50 - 200	100-450	75-250	150-600
Marine Traffic Control Enroute Navigation for Ships	50-400	100-1600	200-5000	400-18,000
Aid to Commercial Fishing	100-1000	150-1500	1000-10,000	3000-30,000

*First number is U.S. owned. Second number is both U.S. and foreign owned.

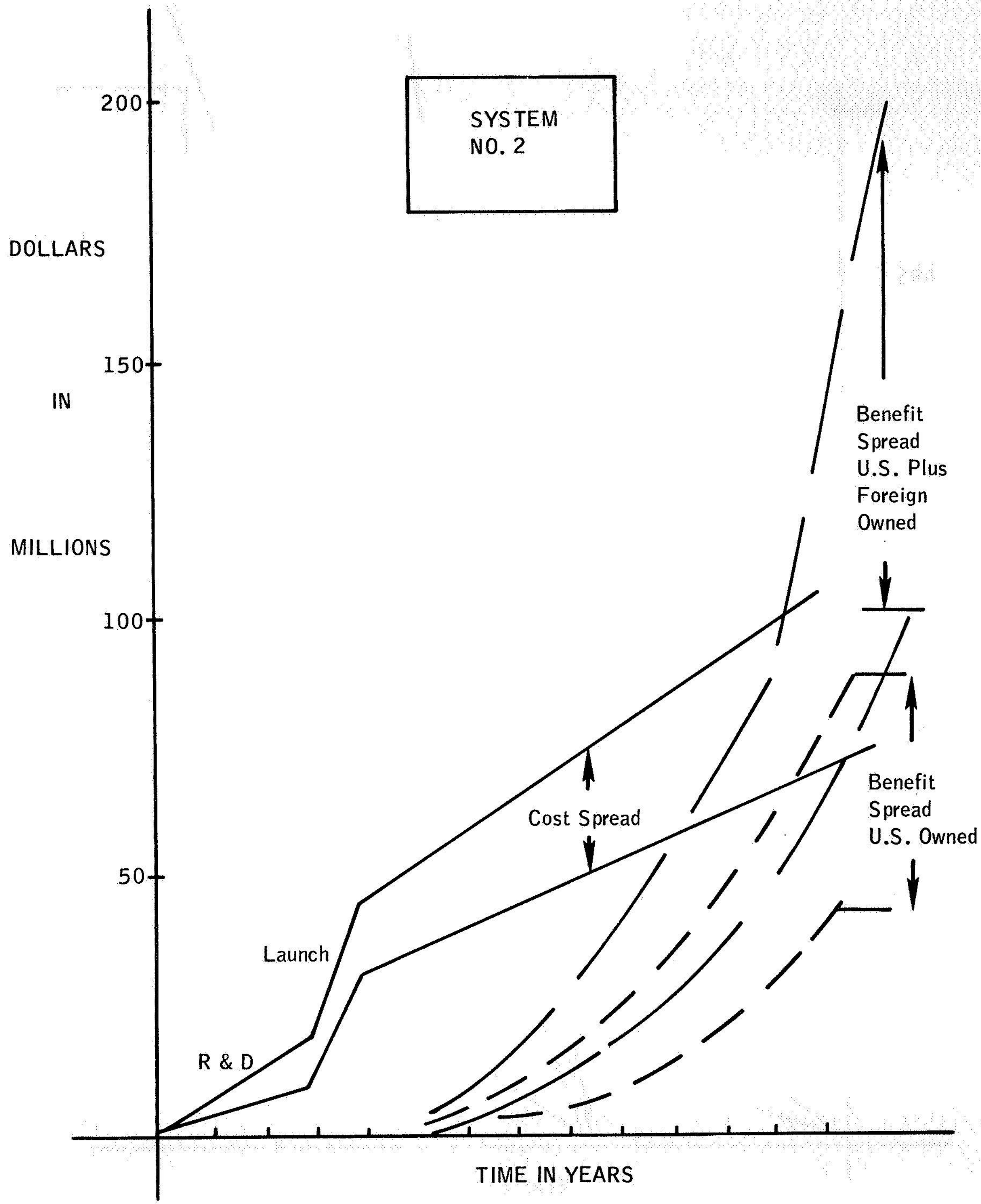


FIGURE 11.8.1 Cumulative cost/net benefits for ten-year period following launch, System No. 2.

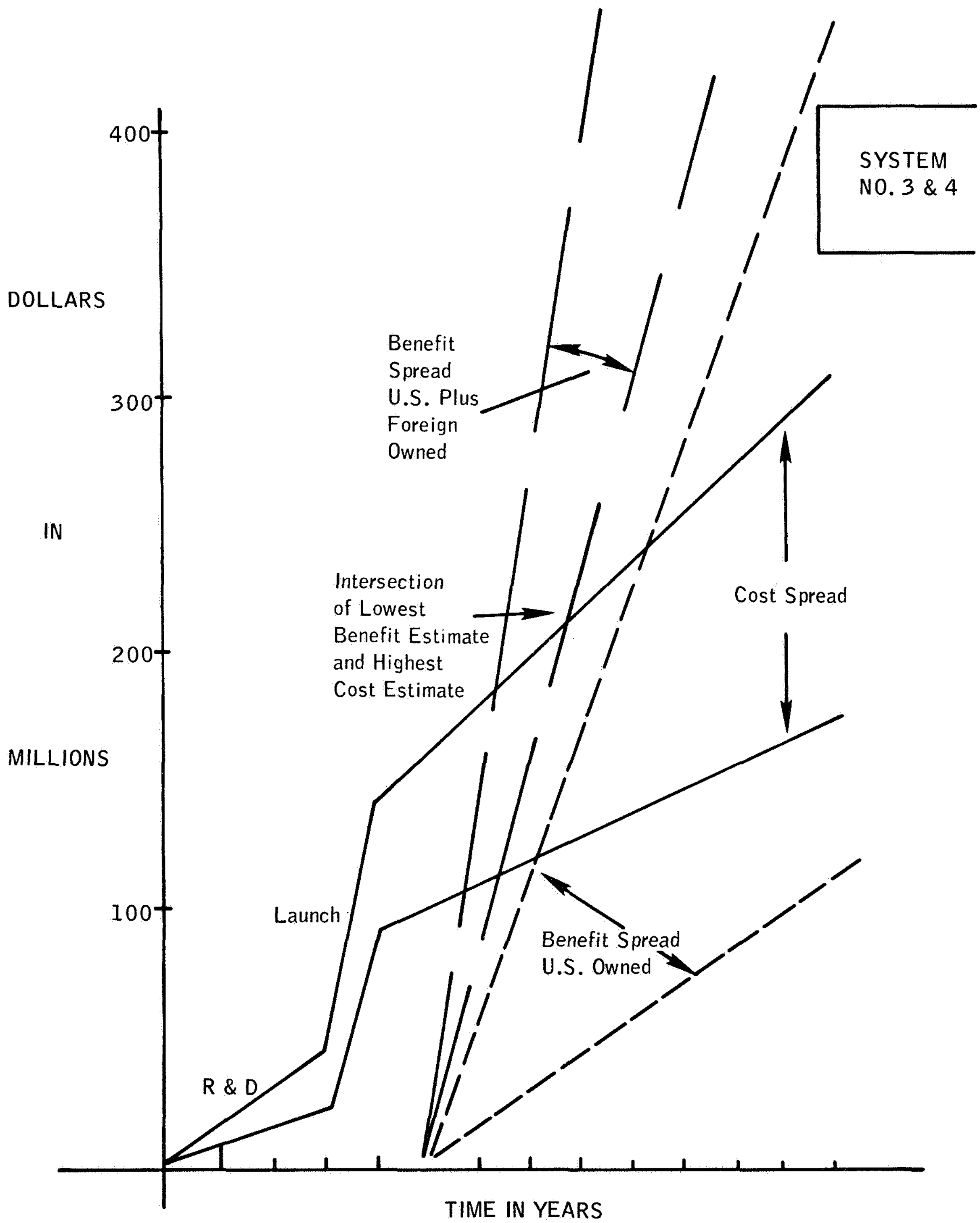


FIGURE 11.8.2 Cumulative cost/net benefits for ten-year period following launch, Systems Nos. 3 and 4.

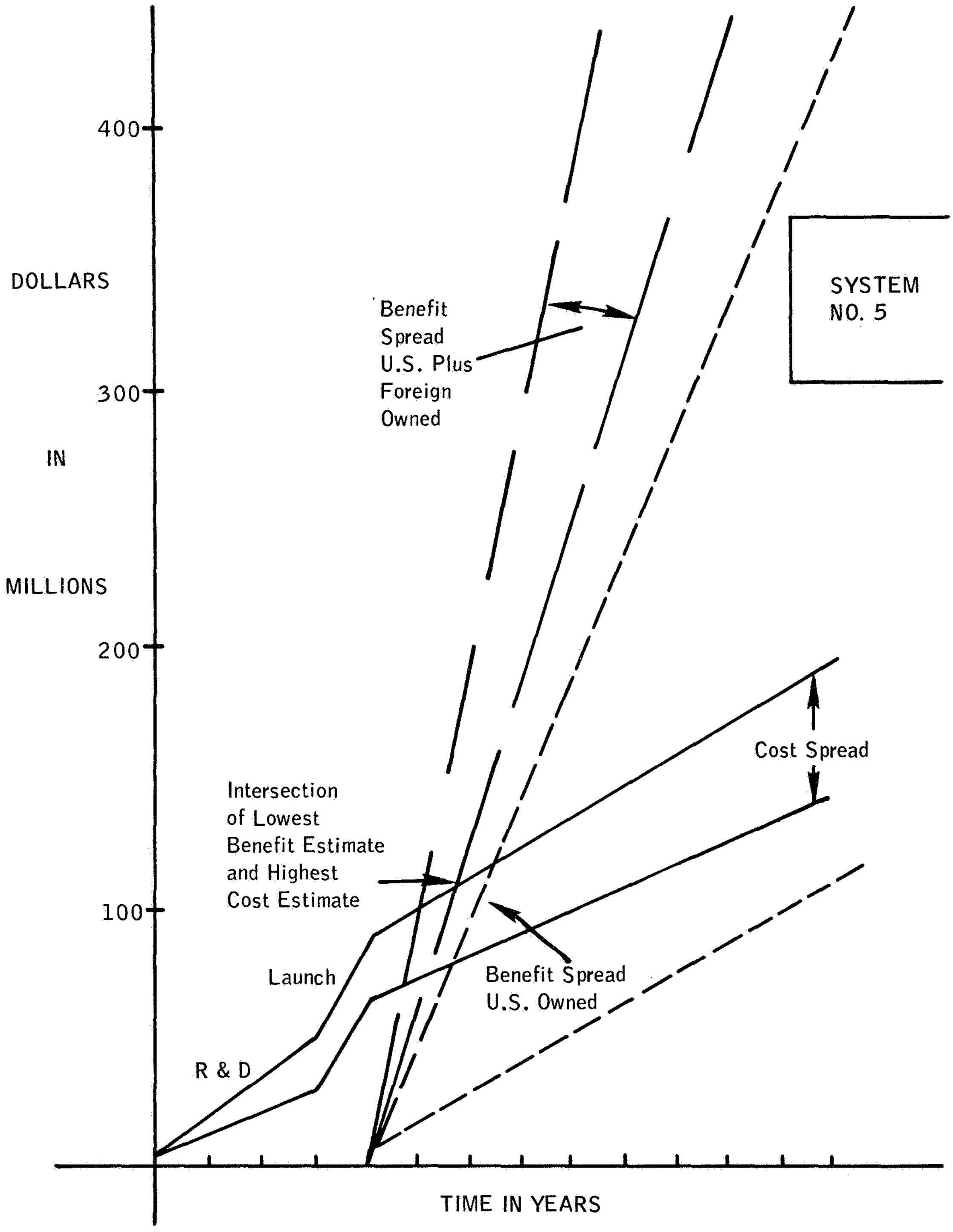


FIGURE 11.8.3 Cumulative cost/net benefits for ten-year period following launch, System No. 5.

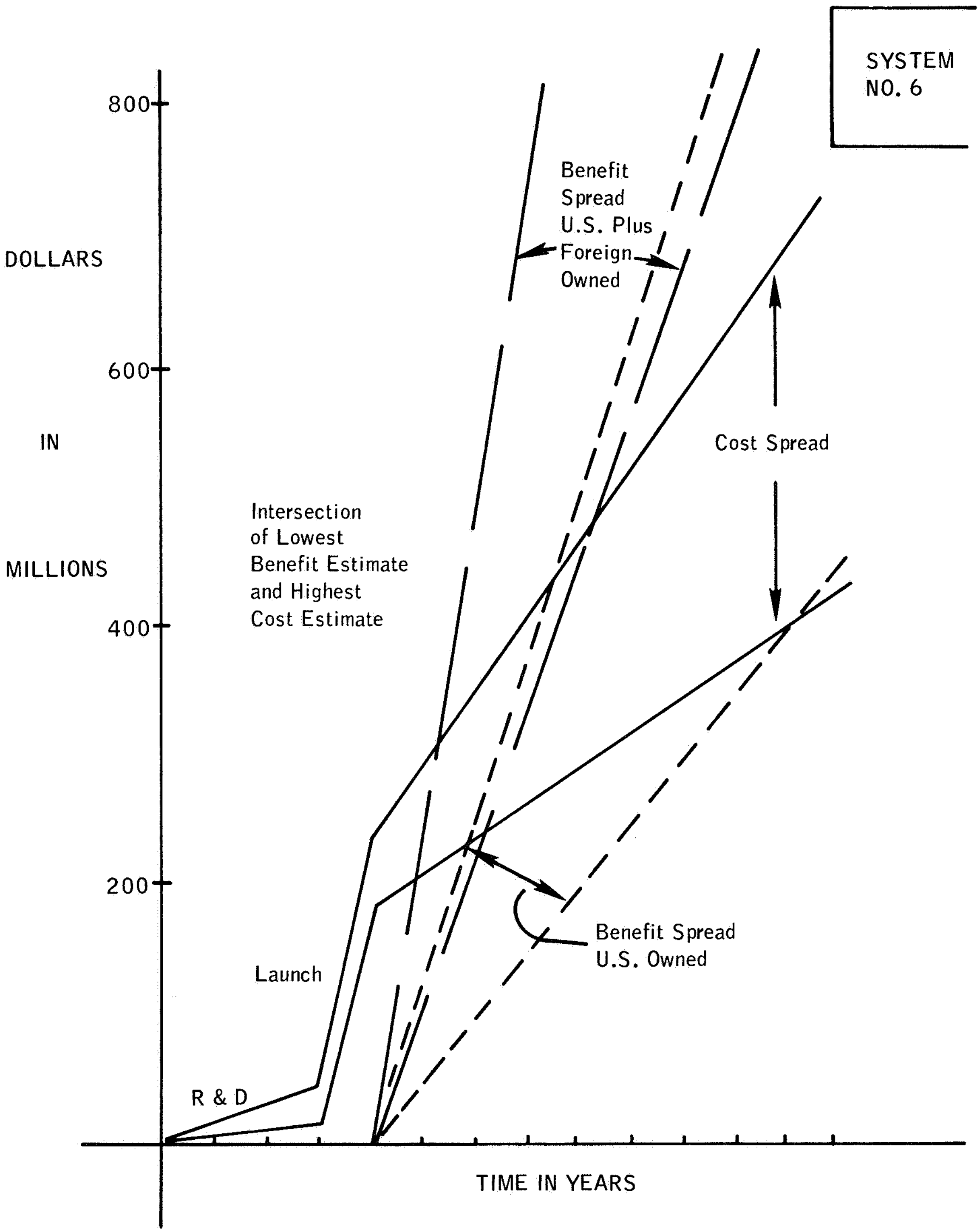


FIGURE 11.8.4 Cumulative cost/net benefits for ten-year period following launch, System No. 6.

9.0 IMPLEMENTATION CONSIDERATIONS

The implementation of satellite systems for navigation and traffic control will require research and development programs, and technical, political, and financial coordination. Policy decisions that have international as well as national ramifications are required. Some of the more critical action areas are described here.

9.1 Technology Development

Some activities in research and development apply to all the systems that are candidates for ultimate implementation; others are uniquely directed towards particular systems. The results of R&D will have vital importance in the decisions relating to their selection. Technical areas which were identified to be of major importance are listed below:

9.1.1 User Equipment

Suitable equipment for mobile station operations with satellites must be developed for almost all of the applications considered. The most difficult and therefore most critical engineering design challenge is aircraft antenna systems. VHF antennas have been developed for subsonic aircraft. Work on designs in the higher frequency bands is vitally needed for all types of aircraft, and VHF designs for supersonic aircraft are not yet available. Long lead times are required if it is to be possible to integrate antenna systems into new types of aircraft at the airframe level. Simple, inexpensive, and reliable antenna tracking systems in the higher frequency bands would be particularly beneficial due to the reduction in satellite power requirements that would result from the use of high-gain steerable arrays by user aircraft.

9.1.2 Ranging Techniques

Experiments with mobile terminals involving various ranging techniques must be performed, using present and future satellites. The evaluation of achievable accuracy and potential usefulness of a line-of-position derived from a single satellite range measurement could be performed in advance of multiple satellite position determination experiments. In assessing performance of such systems in a realistic operating environment, the sum total of errors resulting from propagation effects, modulation system characteristics, and user equipment design should be determined in a statistically significant manner.

9.1.3 Angle-Measurement Techniques

In spite of serious doubts that radio frequency angle measurements can be made to required orders of accuracy (seconds of arc), the potential advantages of systems based upon this principle are important enough to suggest continued research on a long term basis. A space experiment may be warranted in the early 1970's.

9.1.4 Propagation Research

Many of the techniques required in systems under consideration will be most sensitive in their performance to potential phase and amplitude distortion, as well as to propagation velocity uncertainties introduced by the propagation path between the user and the satellite. Statistical data on ionospheric effects and measurement of seawater multipath (which is closely related to user antenna design) are particularly vital.

9.1.5 Systems Analysis

Overall, comprehensive systems-analysis activities will be required in parallel with research and development in key technology areas. Such analysis must include considerations of:

System access and traffic handling procedures

Human engineering of user interfaces

Ground environment organization

Compatibility with established standards

Joint spectrum utilization by aircraft and ships

9.2 Frequency Allocation and Management

Radio spectrum utilization will play a dominant role in the development of navigation and traffic control satellite systems, as in other new satellite applications. As a result of the space Extraordinary Administrative Radio Conference (EARC) of 1963, internationally recognized opportunities for space exploitation in bands 8, 9 and 10 (VHF, UHF and SHF) were developed for aeronautical communications and radio-navigation. However, in the maritime World Administrative Radio Conference (WARC) of 1967, the CCIR was invited to consider only bands 9 and 10 in studies of satellite links with maritime mobile stations. At present, no band is internationally recognized for maritime mobile use with satellites, although the International Radio Consultative Committee (CCIR) has accepted a study question which includes international consideration of joint spectrum usage between aeronautical and maritime services. Early exploitation of satellite techniques for mobile users depends upon use of lower frequencies, but these bands are already heavily used and present substantial coordination problems. As a general rule, the preferred frequency band for satellite links with mobile terminals should be just high enough to avoid unacceptable performance degradation due to frequency-dependent propagation effects. This choice of quasi-optimum frequencies could be considerably different for different system functions (communications, range measurement, angle measurement) and for different types of users. Therefore, some potentially undesirable compromises may be required if a common-usage band is to be selected. The alternative involves consideration of multi-band systems.

9.3 International Considerations

Any satellite system providing navigation and traffic control services will, of necessity, be international in character. The present international agreements and organizational arrangments must be examined to determine their adequacy as a basis for implementing systems. As pointed out in the previous section, there is already some question regarding the adequacy of present international frequency allocations. Although United States leadership in technical development and systems implementation will be essential, the impact of such services will be global in nature, and other states will demand an equal voice in all aspects of such programs. Some areas of concern are discussed here:

9.3.1 Control Responsibilities

At present, there are no international arrangements for Marine Traffic Control, and agreements will be necessary to determine the allocation of operational responsiblities among the interested nations. In the case of aviation, arrangements already exist within the International Civil Aviation Organization (ICAO) for planning and coordinating air traffic services worldwide. Normally, responsibilities are allocated on a regional basis. In some instances, where the responsibilites of a member state for the provision of service are inordinately high compared to its own use, ICAO has coordinated joint financing arrangements. The present regional nature of air traffic services has resulted, in part, from the coverage limitations of existing communications and navigation facilities. Satellite systems, in removing such limitations, will permit geographic consolidation of such services, and so raise questions regarding which member states would assume control responsibilities.

9.3.2 Implementation Responsibilities

International organizational arrangements are essential to the implementation of operational satellite systems intended for worldwide use. One precedent has been set by the organization of the International Telecommunications Satellite Consortium (INTELSAT). This group is cooperating in the establishment of a global communications satellite system under an agreement which provides for ownership according to fraction of system use, and access worldwide on a non-discriminatory basis. Facilities on the ground are owned and operated on a national basis. The success of this arrangement suggests that it may serve as a useful guide in planning the implementation of systems for navigation and traffic control.

9.3.3 System Planning and Standards Coordination

As noted earlier, ICAO is the logical body for coordinating satellite system plans and standards for international aviation, and is assuming this role. A similar activity will be essential for maritime interests in an organization such as the Inter-governmental Maritime Consultative Organization (IMCO). Competent technical advice on radio systems using satellites must be elicited from CCIR.

9.4 Financial Considerations

9.4.1 User Equipments

There has been close to unanimous agreement that each owner of a ship or aircraft will provide the equipment which enables his craft to navigate safely and participate in the benefits of the system. The same principle governs even if international rules require that the equipment be on board and in use for Traffic Control. Matters of lease versus outright purchase, or governmental assistance to subsidized craft, are details, as are the various designs of suitable user equipment which are likely to be built throughout the world.

9.4.2 Capital Costs and System Operating Costs

The matter of who will bear the capital costs and system operating costs has been widely discussed. Several viewpoints are presented below. One proposal is to have an international organization furnish an aeronautical services relay satellite to provide operational and management communications to aircraft over the oceans, employing VHF circuits instead of the present HF circuits. The use of the communications circuits would be subject to a tariff of charges and, presumably, operated at a profit. If a small percent of the total circuit time could be devoted to the making of cooperative measurements of the distance of users from each of two satellites, the position of the users would be known to an accuracy sufficient for Air Traffic Control surveillance purposes. The additional cost would be minimal, and such a system might be the first step in providing a navigation and traffic control satellite system.

The accuracies required for Marine Traffic Control and for navigation appear to require higher frequencies than VHF, probably in the upper UHF band (1.5-2 GHz); and other promising techniques for position determination, such as angle measurement by interferometry, may be competitive with the measurement of distance.

While private financing by venture capital in search of a potential profit has appeal to capitalistic-minded countries, there are ample precedents of large-scale projects such as dams, highways, bridges and irrigation ditches constructed by government from public funds for the overall good of a class of beneficiaries, without repayment by the beneficiaries of any portion of their benefits back to the government.

Indeed, so universal has been the acceptance of governmental support of a navigation and traffic control satellite system that most of the discussion has centered about the question of U. S. government versus true international financing. A navigation and traffic control satellite system is a reasonable candidate for truly international cooperation because of at least two important considerations:

1. The United States owns about 40 percent of the world's trans-oceanic aircraft, but only 10 percent of the world's commercial shipping and perhaps 3-5 percent of the world's fishing fleets. The main beneficiaries of a navigation and traffic control satellite system (as shown in Section 8) will be the other nations of the world, and it appears reasonable that they should provide a share of the capital and operating costs.

2. The international considerations of frequency allocation (Section 9. 2) and of arrangments for Marine Traffic Control (Section 9. 3) will require continuous international support and management if a navigation and traffic control system is to function effectively. An extension of the foregoing would produce the argument that financial support is a responsibility that accompanies management control.

9. 4. 3 Charges to Users of the Navigation and Traffic Control System

While it appears practicable to collect charges from users of a communications system, there has been no general agreement that users of a navigation and traffic control system would be amenable to a tariff.

One shipping company, which operates large tankers, stated a willingness to pay for services which would aid their captains to keep clear of hazards. The TORREY CANYON stranding has been cited as a situation that might have been avoided had a Marine Traffic Control warning been issued to the ship. Other shipping operators are not as sure of the value of the services, and have taken the position of being amenable to payment only after the worth of the service has been established.

The airline industry, on the other hand, has already expressed its opposition to any direct payment for the services of a navigation and traffic control satellite system. This position is in direct contrast to their eagerness to pay for communication services from a satellite, however.

10.0 CONCLUSIONS

1. NASA's programs have been effective in determining the feasibility of a prototype satellite system for navigation and traffic control; e.g., various system studies and Applications Technology Satellite (ATS) experiments.

2. It is feasible, with present technology, to establish satellite systems for navigation and traffic control of ships and aircraft. (Nevertheless, research and development are needed on a continuing basis to improve the technology and reduce the cost of future systems.)

3. The U.S. Navy's TRANSIT satellite navigation system adequately fulfills its intended purpose, but is not applicable to non-military air and marine traffic control.

4. The most useful applications of a satellite system for navigation and traffic control are:

   a. En route traffic control of transoceanic aircraft

   b. Traffic control of surface vessels in confluence areas

   c. Search and rescue at sea (air as well as marine)

5. On technical and engineering grounds, satellite systems are superior to systems now in use in the aforesaid applications. However, satellite systems do not now offer advantages over the other available systems for terminal air traffic control and harbor traffic control.

6. The principal benefits which would ensue from the use of a satellite navigation and traffic control system are:

   a. Faster search and rescue at sea

   b. Improved traffic flow of aircraft over high-density trans-oceanic routes

   c. Reduction in ship collisions and strandings

   d. Savings in operating costs of shipping lines

   e. Increased efficiency in commercial fishing

7. The costs of a satellite system to provide only en route transoceanic air traffic control would exceed the quantifiable benefits to be gained for many years. On the other hand, such a satellite could also provide improved operational and management communication services to aircraft; and these benefits might make the satellite system cost-effective at an earlier period.

8. The benefits received by the overall marine community from a satellite system to provide traffic control in confluence areas and en route navigation for ships would exceed the costs of such a system. Most of these benefits would accrue to foreign-owned ships, because the U.S. - owned fleet is relatively small.

9. In general, the cost-benefit advantages to the maritime industry greatly exceed those to the aviation industry. However, these advantages can accrue to the marine and aviation industries simultaneously from the same satellite system.

10. Conclusions 7, 8, and 9 are conservative in the following two respects:

a. These cost-benefit analyses are based upon present technology, without taking into account future technical developments which may reduce costs.

b. These cost-benefit analyses use only those benefits which are quantifiable. In addition, there are significant non-quantifiable benefits.

11. The earliest realizable operating system seems to be a single geostationary satellite over the North Atlantic, using VHF channels for ranging, to monitor the positions of aircraft approximately at right angles to their lanes. This system would use roll-call access, with an emergency channel. This could be followed by additional similar satellites to determine positions along-track as well as cross-track. UHF satellites of the same type might follow. Eventually, satellite systems which use angle-measurement techniques could replace the ranging systems.

12. A responsible agency (or agencies) should establish technical development plans, recommend national policy, and foster international cooperation and agreement, in order that an operating satellite navigation and traffic control system be implemented for trans-oceanic air and marine vehicles.

11.0 RECOMMENDATIONS

11.1 System Development

Design, build and test a developmental system to provide traffic-control service to en route navigation for ships, using geostationary satellite and ranging measurements for position determination. The principal objectives of this system should be to demonstrate operational feasibility and seek ways of reducing costs.

11.2 Research and Development

The following areas of research and development should be pursued concurrently with the system development of item 11.1 above. These are the areas of R&D which are most needed for the development of improved navigation and traffic control satellite systems:

1. Improved Aircraft Antenna Systems for Use with Satellites

Develop aerodynamically-clean VHF antenna for supersonic aircraft. Develop UHF antennas for all types of aircraft. Determine the practical limits on the gains of UHF antennas, in order to determine the economic practicality of providing voice communications. Design objectives should include coverage of the entire upper hemisphere, and minimization of seawater multipath effects.

2. Radio Propagation

Propagation research is needed in two areas. The first involves a determination of the statistics of uncorrectable range errors induced by the ionosphere in the VHF and UHF bands. An inventory of the present body of ionospheric knowledge may indicate the need for additional experimental research. The second area involves experimental determination of the effects of seawater multipath on satellite-to-aircraft links using aircraft antenna systems with characteristics expected in operational use.

3. Angle-Measurement Techniques

Research and development should be pursued to explore the advantages of angle-measurement systems at radio frequencies.

11.3 Related Research and Development

Continued support should be given to research and development programs aimed at improving the efficiency of power generation, as well as conversion of DC to RF power. Satellite power efficiency takes on particular importance in systems serving small users, due to the relatively high power levels required for transmitting to such users. The same consideration applies to small unmanned platforms (such as buoys, balloons, and animals under study) that transmit to the satellites.

11.4 Systems Analysis and Definition

In addition to 11.1, 11.2, and 11.3, a detailed program of system analysis and design should be conducted, in coordination with potential operating and user groups. Such studies should include consideration of:

Frequency selection and coordination

System access

Satellite orbit configurations

Satellite design

Organization of ground complex

Modulation techniques and message formats

User equipment standards and system interfaces

System economics

Traffic control procedures

Continuing comparison with competing systems

11.5 Implementation Planning

The following are recommended to insure the timely establishment of satellite systems for navigation and traffic control:

1. A national policy statement of objectives, roles and responsibilites in planning, implementation and operation, and a supporting plan
2. A technical development plan
3. A determination of frequency requirements in adequate detail to permit initiation of all necessary national and international coordination activities
4. Initiation of necessary international negotiations and arrangements

THE NATIONAL ACADEMY OF SCIENCES is a private, honorary organization of more than 700 scientists and engineers elected on the basis of outstanding contributions to knowledge. Established by a Congressional Act of Incorporation signed by Abraham Lincoln on March 3, 1863, and supported by private and public funds, the Academy works to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance.

Under the terms of its Congressional charter the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and antonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U.S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial, and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.